from astrophysics to fusion plasmas: signal processing and system optimization analysis for ITER

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OUTLINE

- a brief introduction to the physics of thermo-nuclear fusion plasmas:
  - one challenge: measure magneto-hydrodynamic instabilities in tokamaks
  - **why we must do this in real-time**
- the mathematical methods:
  - from astronomy and astrophysics to thermo-nuclear fusion plasmas
  - real-time analysis of Alfvén Eigenmodes in JET
  - measurement requirements, system optimization, signal processing and real-time control aspects for Alfvén Eigenmodes in ITER
- summary and conclusions, **ideas for discussion**:
  - back to astronomy and astrophysics: "real-time" data analysis processes for the SKA telescope
  - and something more: archaeological prospection techniques

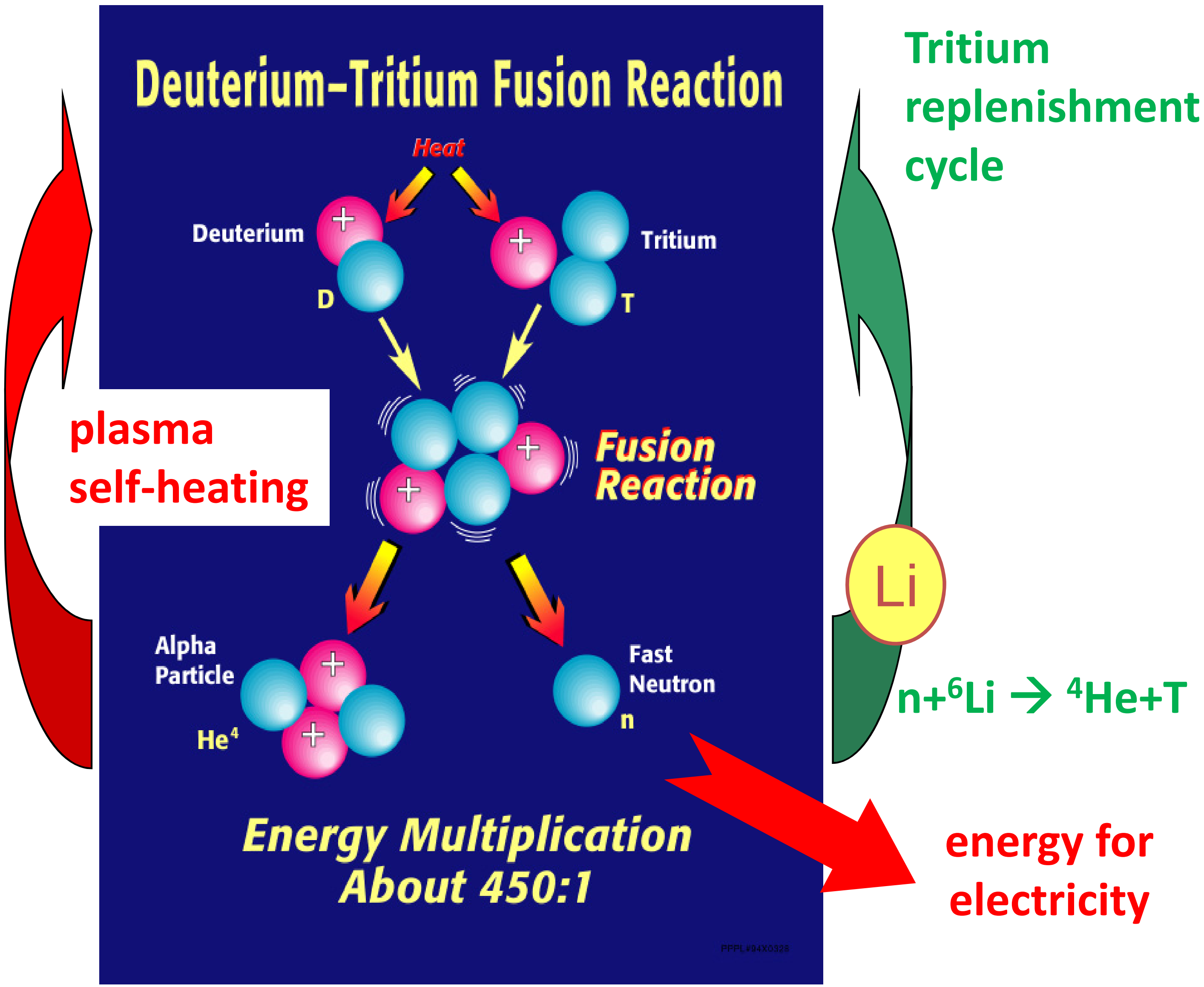
A VERY BRIEF INTRODUCTION TO THERMO-NUCLEAR FUSION IN MAGNETICALLY CONFINED DEVICES

the goal: use thermo-nuclear fusion to produce electricity

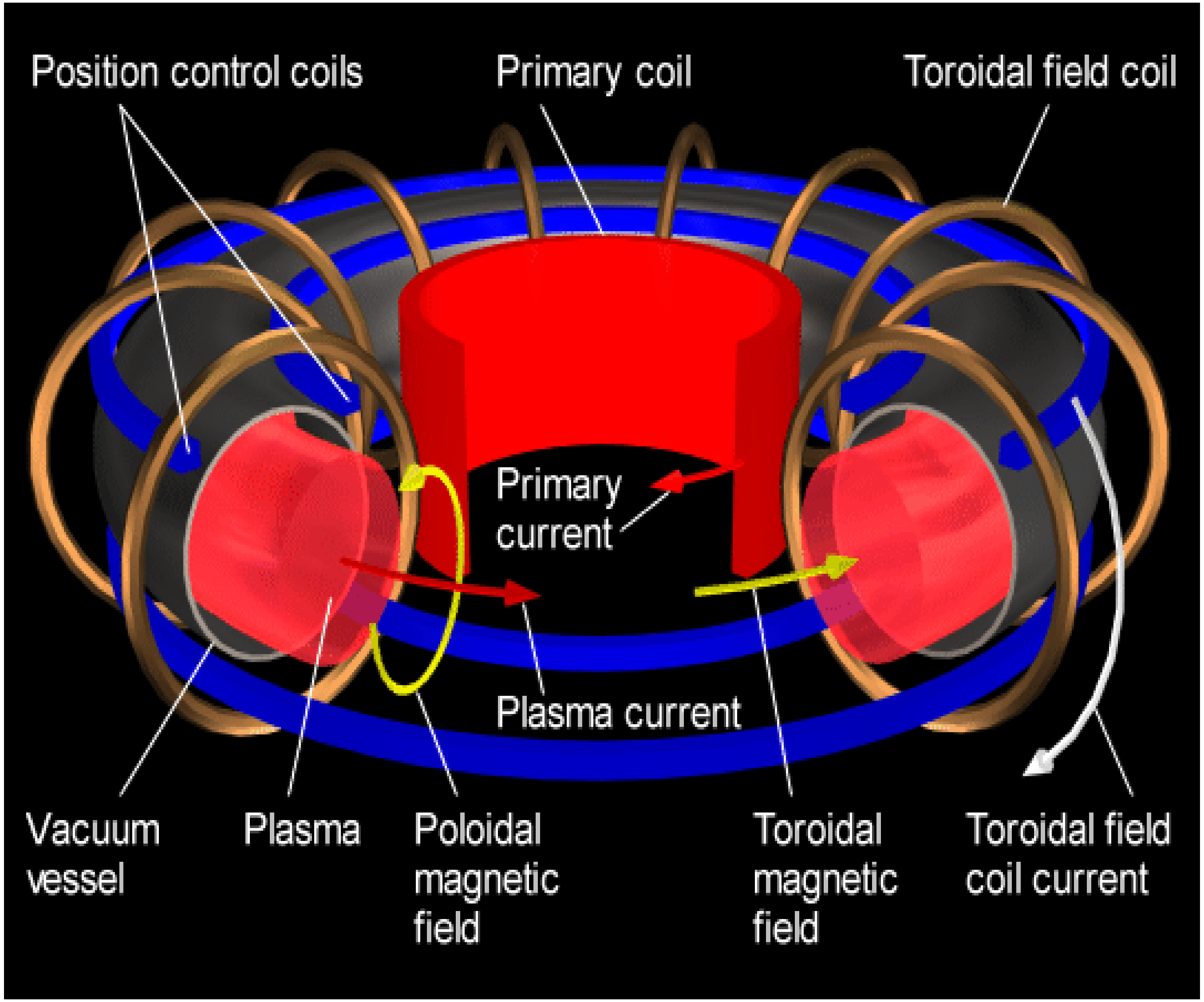
$D+T \rightarrow {}^4He(3.5MeV) + n(14MeV)$

- in stars: big size ➔ plasma confinement by gravity
- on Earth: small size ➔ plasma confined with magnetic fields
- DT fusion has the highest cross-section in the relevant parameter range ($n \approx 10^{20} m^{-3}$, $T \approx 20 keV$)

➔ <u>requires fusion-born αs to remain confined to produce a net energy gain</u>



one method for plasma confinement with magnetic fields: the tokamak concept



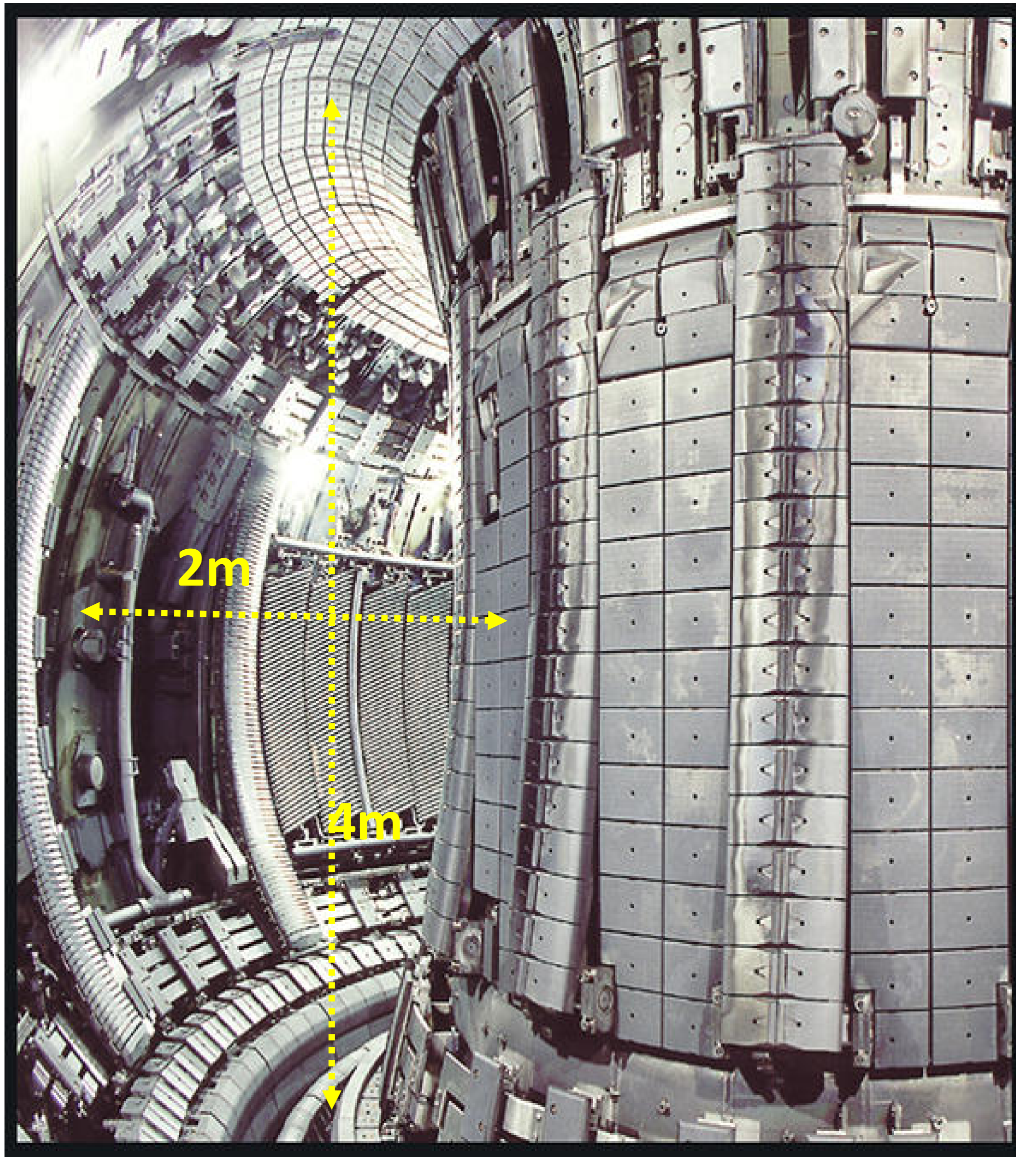
- 3D magnetic field geometry
- 2D plasma current
- 2D plasma pressure
- all with spatial gradients

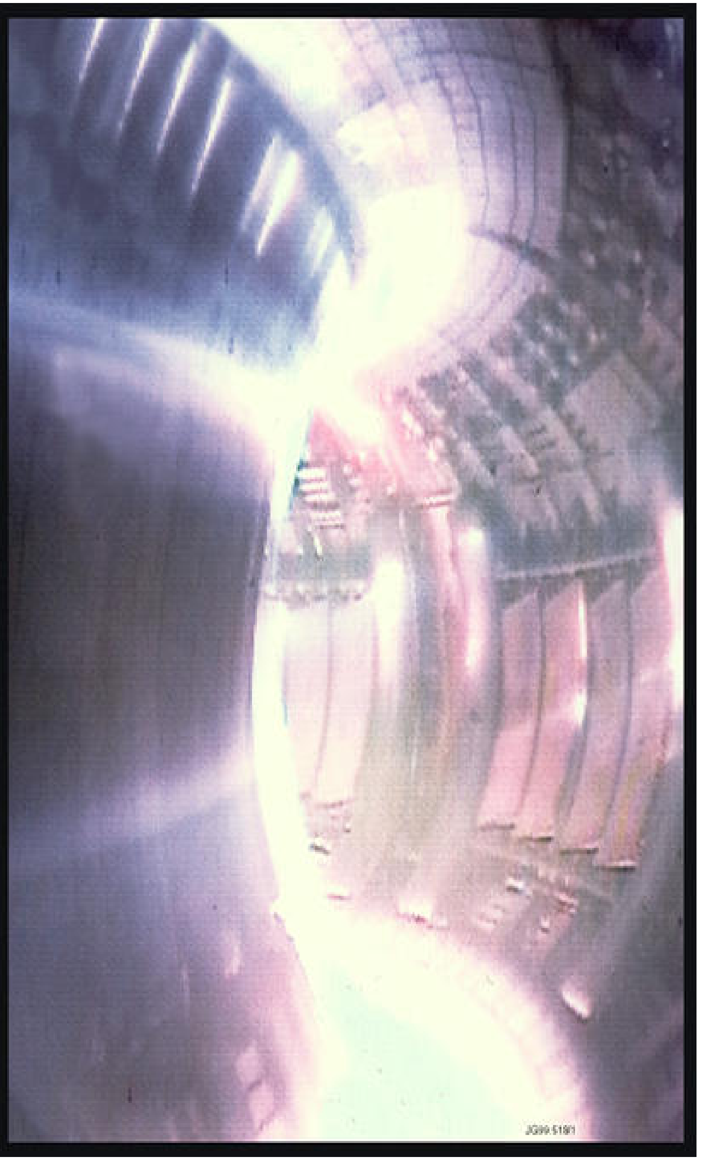
- two main stability parameters:
- pitch of the B-field lines (q)
- kinetic-to-magnetic pressure ratio (β)

➔ magnetic field and plasma frozen together: field lines ≡ strings with tension and inertia

- one (of a few ...) source of instability: too large $\nabla\beta$ for certain ion plasma species at *bad* q-values
  - Alfvén Waves: natural Eigenmodes of any magnetically confined plasma
  - cannot be avoided
  - must be measured and controlled

an existing tokamak: the Joint European Torus (JET)





- plasma volume =80m^3
- max(B)=4T
- max(I_p)=6MA
- maximum fusion gain Q=0.65 transient
- maximum fusion gain Q=0.35 steady-state
- maximum fusion power P_{FUS}=16MW
- D, H, He and DT plasmas
- 60sec maximum pulse length (engineering limit on magnets cooling)
- **pulse repetition rate: 20 to 30 minutes**
- **~5GB data/pulse, ~½ for MHD analysis**
- **+ ~40Gb data/pulse for high-resolution cameras**

EFDA JET

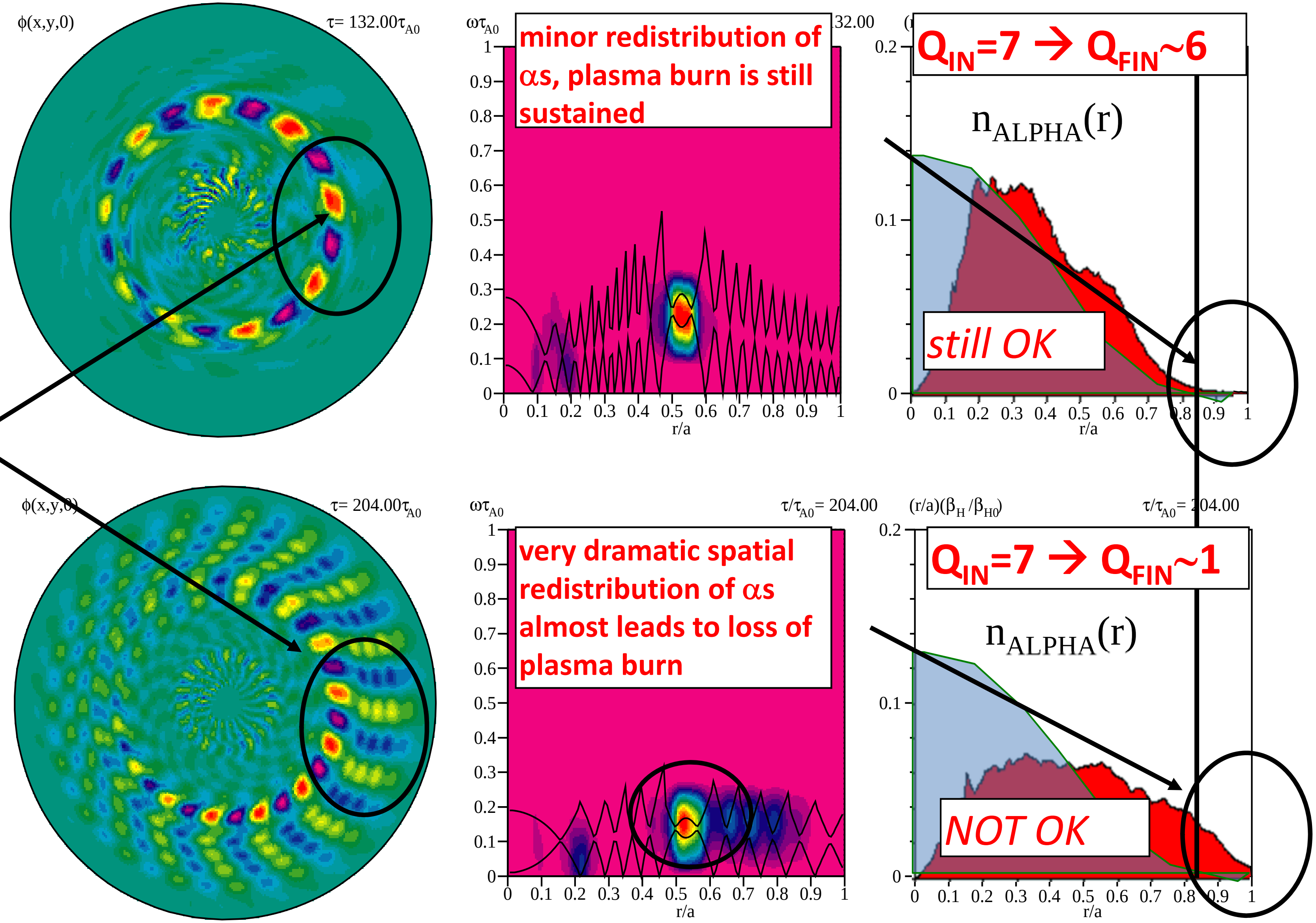
one challenge: Alfvén Eigenmodes

αs generate instabilities that can reduce energy gain

single instability interacting with αs

need reliable real-time detection of potentially "detrimental" α-driven instabilities for active feedback control

multiple instabilities interacting with αs ➔ fast evolution on time scales $\approx 100\tau_A \approx$ faster than 1msec



METHODS FOR REAL-TIME ANALYSIS OF MHD MODES IN TOKAMAKS AND THE SPARSE REPRESENTATION OF SIGNALS

challenges for the measurement and analysis of magnetic instabilities in fusion experiments

- **multiple degenerate modes** expected at nearly the same frequencies
- **need precise determination** of mode characteristics
  - active feedback control and plasma spectroscopy
- **uneven spatial sampling must be applied**
  - spatial Nyquist criterion cannot be used due to engineering/financial constraints
- **must conserve phase relation between I/Q components of measured fluctuation spectrum**
  - stable vs. unstable instabilities, damping and growth rate
- **blind analysis**, no previous knowledge of fluctuation spectra can be used
- **must use a deterministic, physics-based approach, not probabilistic**
  - issues of nuclear safety and protection of investment
- **real-time applications require <1ms clock-rate**

➔ **methods from astrophysics help thermo-nuclear fusion in tokamaks!**

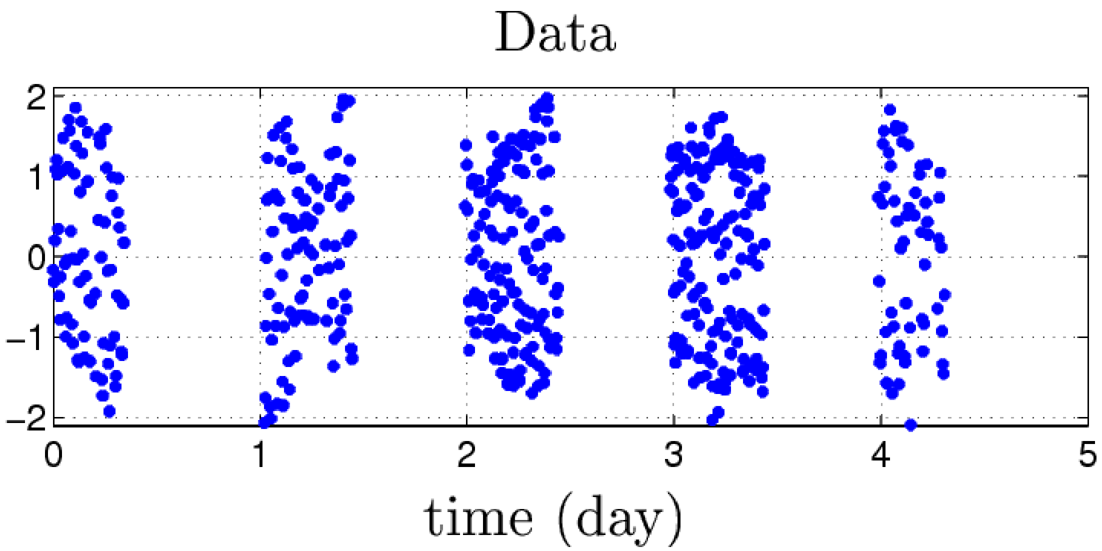
problem statement -1

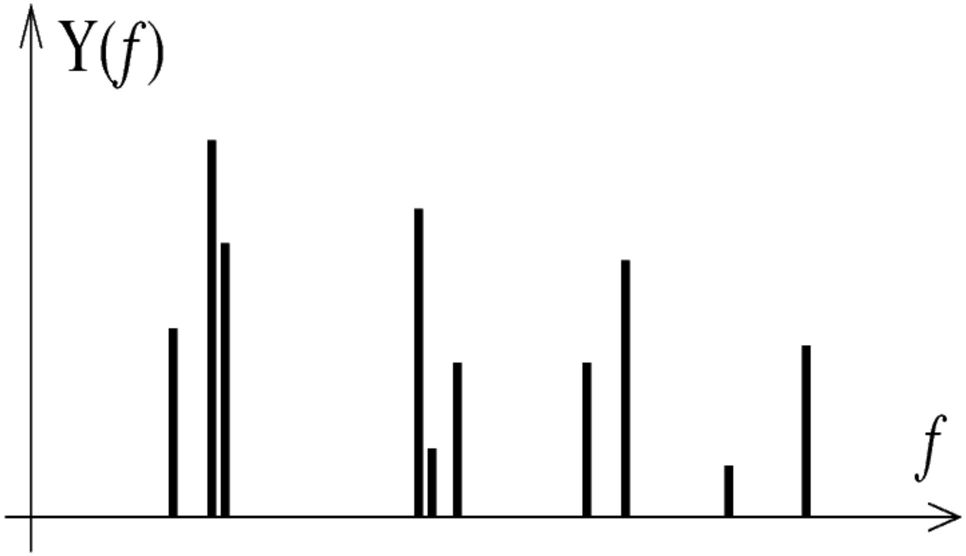
- astrophysical time-series analysis
  - light curves, radial velocity ...
  - observational constraints: day/night alternation, meteorological conditions

➔ **irregular sampling**

- looking for periodicities
  - variable stars: several oscillation modes
  - multiple stars system: a few periods related to the orbits

➔ **estimation of spectral lines**





problem statement -2

- mathematical modelling: parameters (ν_l, c_l), l=1, ..., L

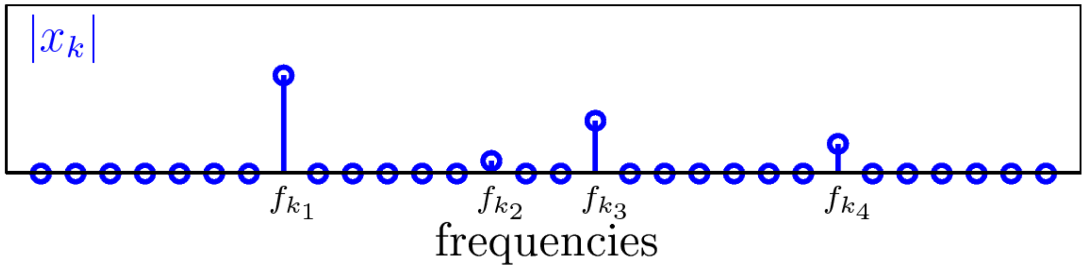
$$y(t_p) = \sum_{\ell=1}^{L} c_\ell \, e^{2j\pi\nu_\ell t_p} + \epsilon_p$$

☹ Non linear w.r.t. ν_ℓ ; ☹ L unknown

- discretization of the frequencies axis: $f_k=(k/K)f_{MAX}$, k=-K, ..., K

$$y(t_p) = \sum_{k=-K}^{K} x_k \, e^{j2\pi f_k t_p} + \epsilon_p$$

☺ linear w.r.t. x_k $\leftrightarrow$ ☹ large number of unknown (high value for K)



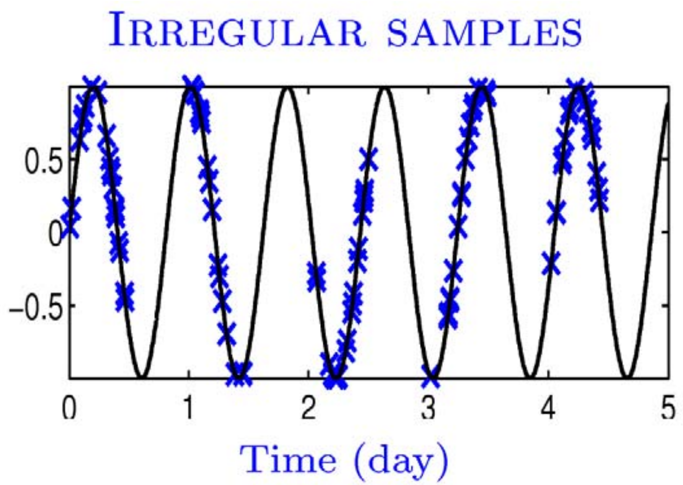
- estimation of spectral lines ➔ prior information: enforce sparsity of $\{x_k\}_K$

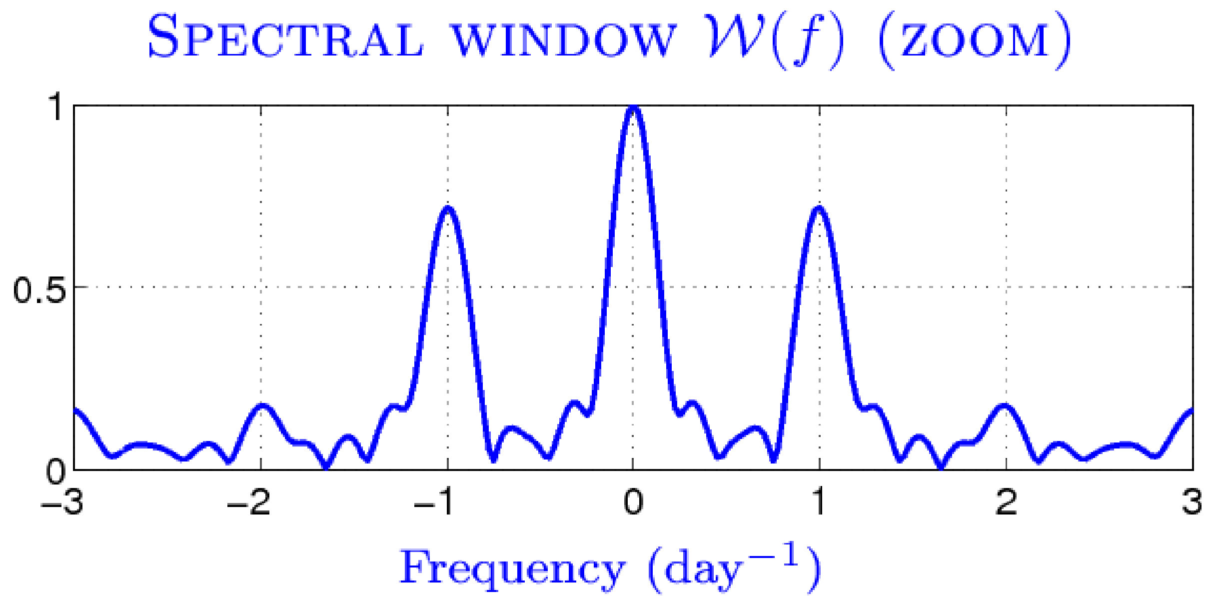
problem statement – spectral window

- irregular sampling: data filtered with Dirac-type windows

$$y_s(t) = \begin{cases} \sum_{p=1}^{P} y(t_p)\delta(t-t_p) & \xrightarrow[\text{Transform}]{\text{Fourier}} \quad Y_s(f) = \int_{-\infty}^{\infty} y_s(t) e^{-2j\pi f t} dt = \sum_{p=1}^{P} y(t_p) e^{-2j\pi f t_p} \\ y(t) \times \underbrace{\sum_{p=1}^{P} \delta(t-t_p)}_{w(t)} & \xrightarrow[\text{Transform}]{\text{Fourier}} \quad Y_s(f) = Y(f) \star \underbrace{\sum_{p=1}^{P} e^{-j2\pi f t_p}}_{\mathcal{W}(f)} \end{cases}$$

➔ <u>**a deconvolution problem!**</u>





problem solution: the Sparse Representation Method and the SparSpec* code

$$\boxed{J(x) = \tfrac{1}{2}\left\|\mathbf{y} - W\mathbf{x}\right\|^2 + \lambda \sum_{k=-K}^{K} \left|x_k\right|_{L1}}$$

the SparSpec code minimizes the L1-norm penalized criterion

y: vector of data taken at time t_k [≡ position ϕ_k]
W: spectral window $\exp(i2\pi t_k f_n)$ [≡ $\exp(i2\pi\phi_k n)$]
x: vector of (I,Q) signals for frequencies f_n
λ: parameter fixed to obtain a satisfactory sparse solution ➔ **penalty criterion for invoking more modes to find adequate solution**
λ can be fixed a-priori from known noise variance

- Sparse Representation method applied here not in its usual format:
  - inverse problem: we want **x**, not the approximation **Wx**
  - dictionary driven by the physical problem (≡exp) not by mathematical functions

➔ **physics-based interpretation of L1-norm penalization criterion**

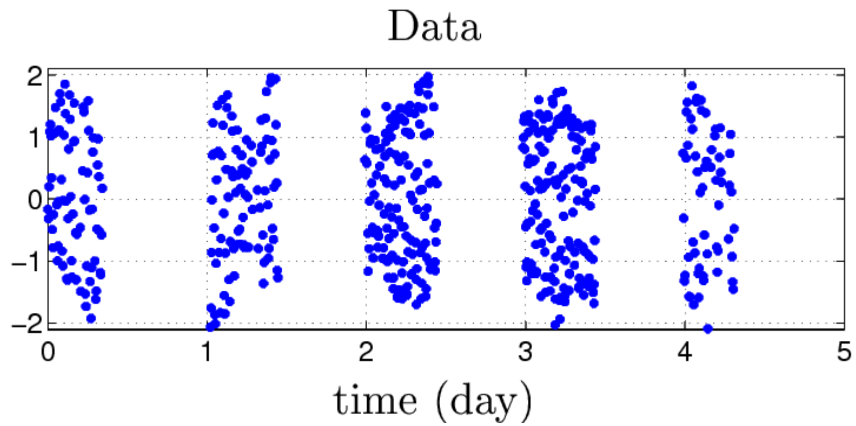
➔ **very efficient, very fast convergence (BCD algorithm)**

➔ **the same algorithm can be used in real-time and post-pulse**

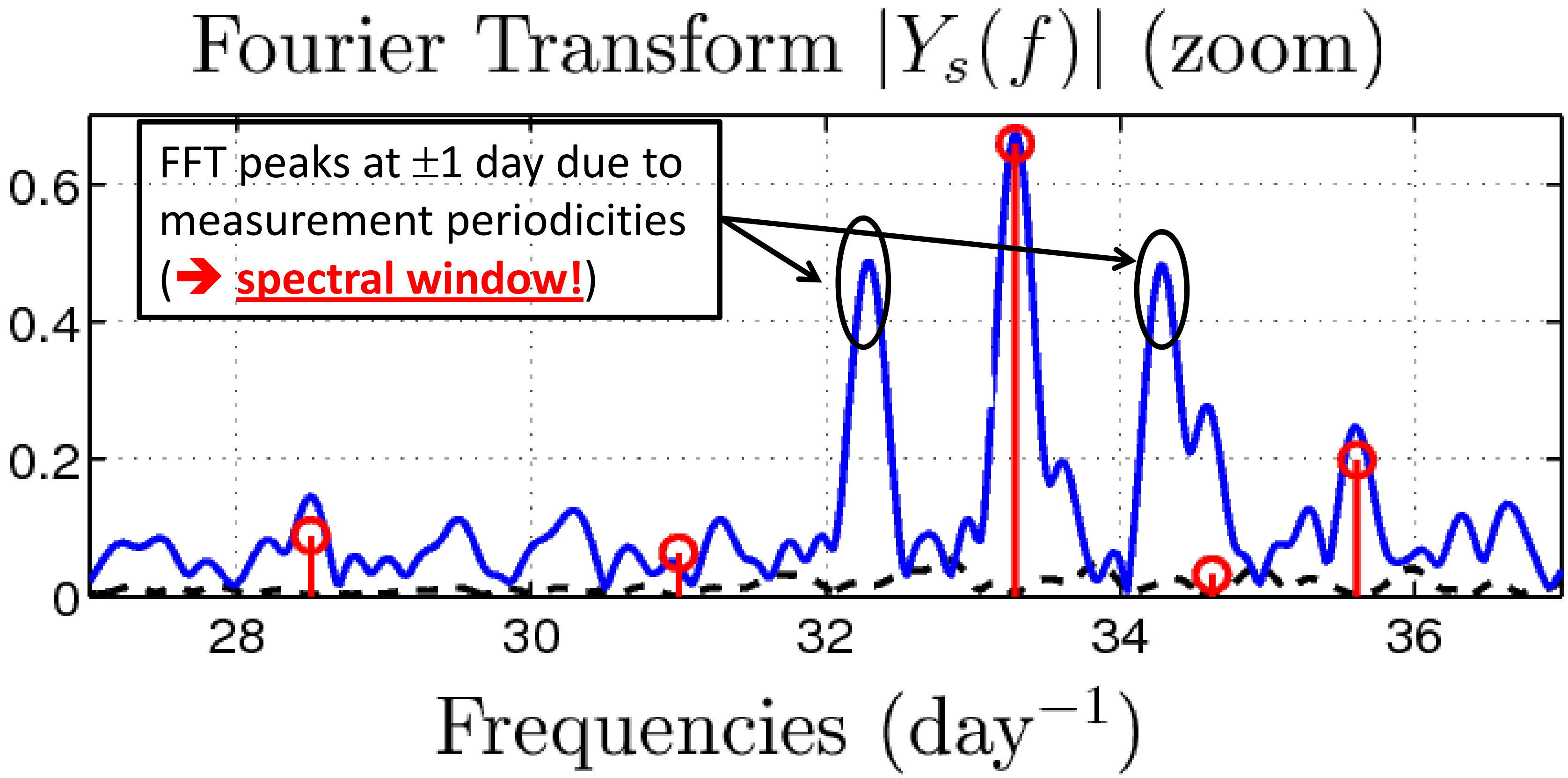
* S.Bourguignon, H.Carfantan, T.Böhm, Astronomy and Astrophysics **462** (2007) 379: **"SparSpec: A New Method for fitting multiple sinusoids with irregularly sampled data"**, http://www.ast.obs-mip.fr/Softwares

SparSpec for astronomical data

- observation for the radial velocity curve of the Herbig Ae star HD 104237
- these data correspond to five observing nights of high resolution spectroscopy at SAAO (South African Astronomical Observatory) during April 1999



- low-frequency perturbation due to various orbital movements are removed



thermo-nuclear fusion: differences with the astrophysical problem

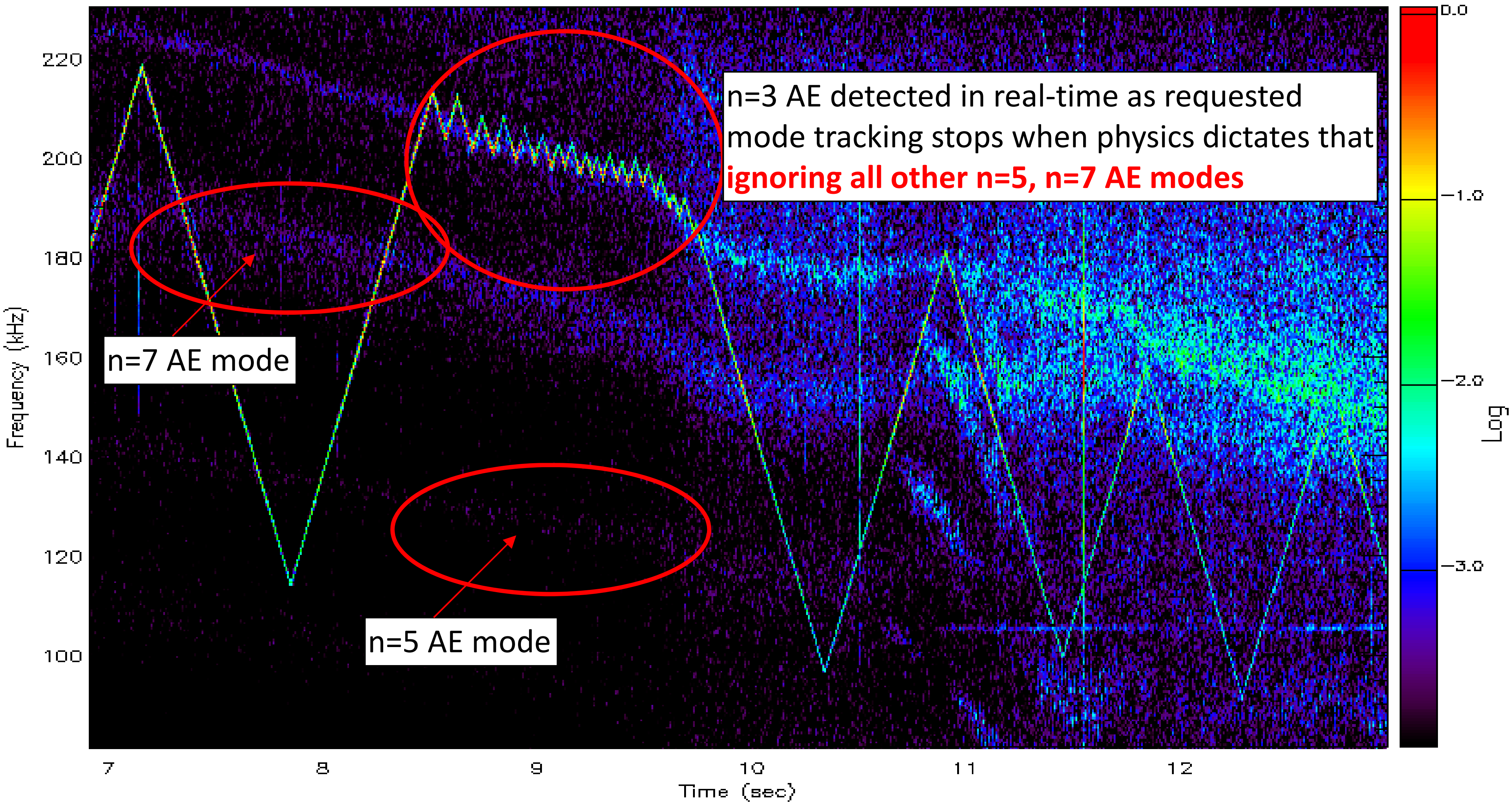
	astrophysics	thermo-nuclear fusion
model	$y(tp) = \sum_{l=1}^{L} \alpha_l \exp(-2\pi i \nu_l t_p)$	$y(\phi_p) = \sum_{l=1}^{L} \alpha_l \exp(-i n_l \phi_p)$
data	real valued $y_p \in R$	complex valued $y_p \in C$
number of data	large: in excess of thousands	**small to medium: from 10 to 50**
mean value of data	to be removed: mean luminosity, weather/seasonal variations, ...	to be kept as it corresponds to vertically unstable plasmas
detection	frequencies $\nu_l \in R$ (outside the discretization grid)	frequencies $n_l \in N$ (exactly on the discretization grid)
computational time	not limited	**real-time requirements (1msec)** not limited post-pulse

➔ **SparSpec algorithm now implemented in JET for analysis of Alfvén Eigenmodes, post-pulse and real-time**

the real-time Alfvén Eigenmodes diagnostic

- “hard” (fail-safe) real-time embedded system: problem ≡ termination
- uses frequency sweep provided by in-vessel antennas to detect the modes and track their real-time evolution
- synchronised experiment events and 1kHz clock distribution card
- four 16-channel analogue to digital conversion (ADC) cards
- two processor cards:
  - a communications CPU to manage all the asynchronous communications and events using a 400MHz PowerPC with 64MB RAM
  - a real-time CPU dedicated to extracting and processing data from the ADC cards within strict <850μsec time constraints using a 1GHz PowerPC with 512MB RAM
  - *overall rather modest computing resources ... my laptop does better!*
- uses the WindRiver VxWorks operating system
  - as used in NASA’s Mars rovers, Spirit and Opportunity

real-time tracking using SparSpec



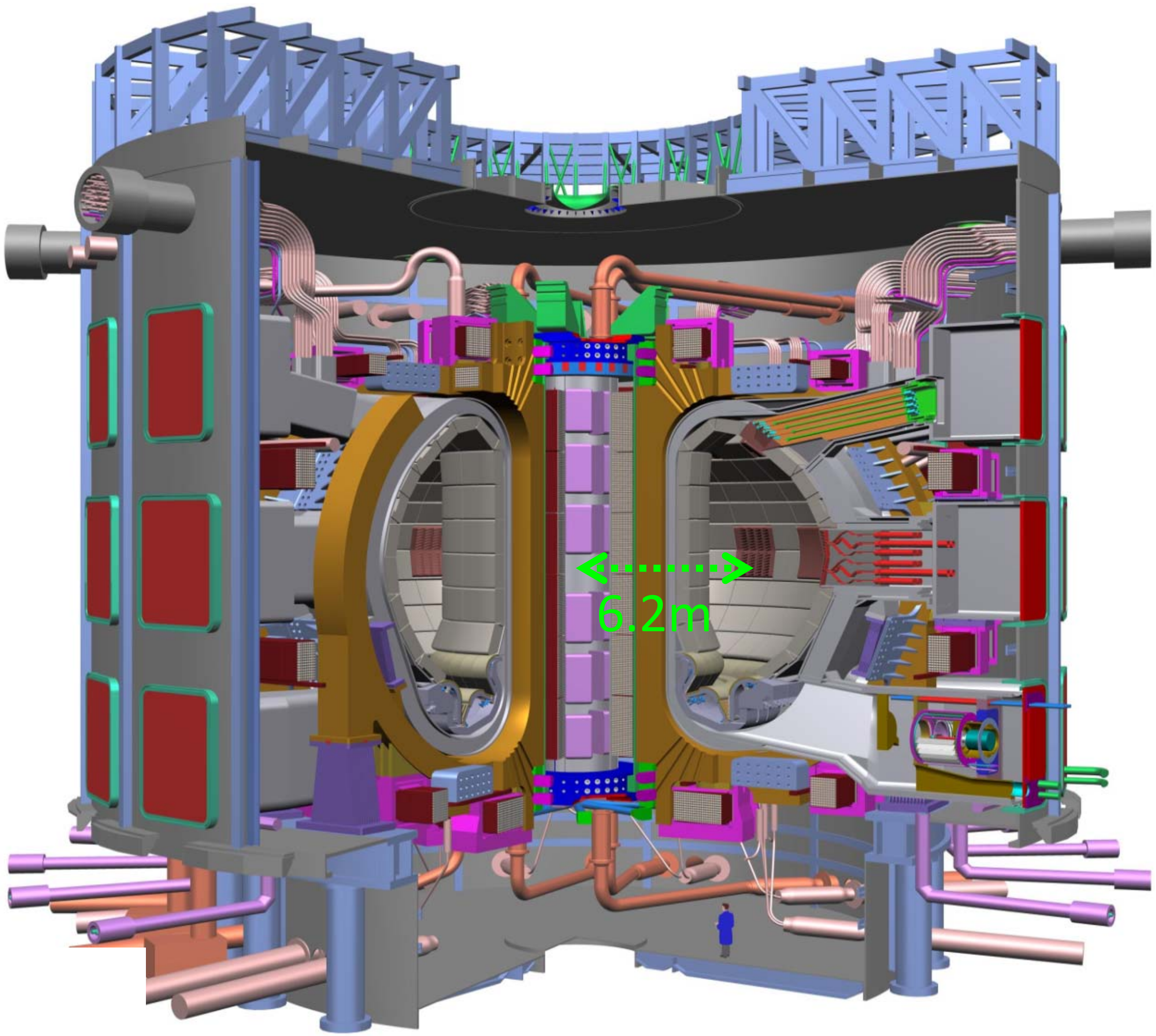
- **real-time identification and tracking of specific modes using algorithm based on SparSpec code, with 1ms clock-rate (<850μs CPU)**

DATA ANALYSIS REQUIREMENTS FOR ITER

a forthcoming tokamak: ITER

official goal: to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

- the 7 partners in ITER: EU, USA, Russia, China, Japan, Korea, India
- the role of ITER
  - burning plasma physics: pulse length >1000sec, $P_{FUS} \geq 500MW$ for >500s, $Q \geq 10$, $T \approx 20keV$, $n \approx 10^{20} m^{-3}$
  - full integration of physics and technology
  - demonstrate fusion power plant control and safety
- ITER construction has started
- first plasma foreseen in 2019
- first experiments with DT plasma aiming for Q>1 from March 2027



$R=6.2m$; $max(B_T)=5.3T$; $max(I_p)=15MA$

the way to new energy

iter

china eu india japan korea russia usa

control and command requirements for ITER

- the ITER Control-Command has to fulfil three distinct missions:
  - **safety**, since ITER is a nuclear device
  - **protection of investment**, since ITER is (relatively...) expensive (~20 billion euros over 30 years)
  - **experiments**, since ITER is a research project

- the ITER Control-Command also has two distinct layers:
  - proprietary equipment developed by the project team at the ITER site
  - equipment provided "in kind" by the seven partners

- the ITER Control-Command also has two main components:
  - Control, Data Access and Communication System: ~500'000 signals on 500msec clock
  - Plasma Control System: ~1'000 signals on 500μsec clock (real-time processing)

- ITER scientific research will be international, data have to be international, like CERN, but operation has to be under French regulatory control

- about **45 parameters** have to be measured for ITER operation
- expecting in excess of 60TB of data for each ITER pulse of 1'000 seconds
- physics and engineering integration: measurement specifications guide the design of the corresponding diagnostic systems, within allocated budget

ITER control, data access and communication system

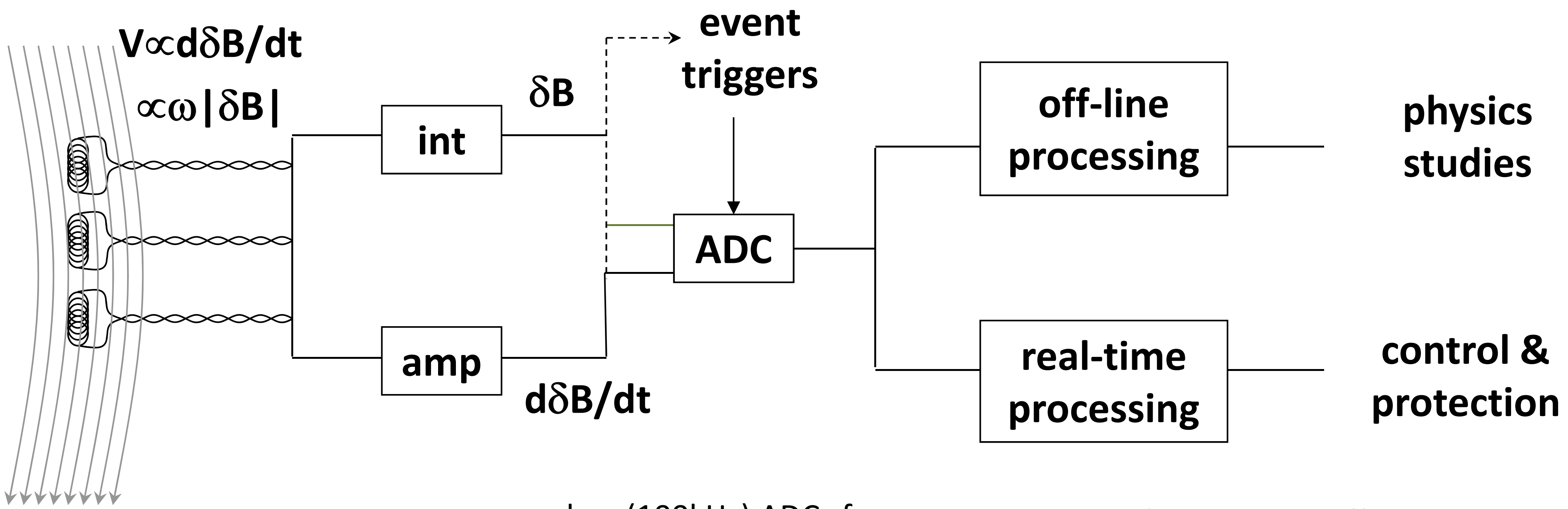
- the ITER Control, Data Access and Communication system (CODAC) provides the experimental component of the Control-Command on the slow 500msec timescale:
  - integrate ~150 independent sub-systems
  - monitor >500'000 signals between 0.1Hz and 1MHz
  - control tens of 1000's of real-time actuators
  - ensure logical sequences to functionally integrate each of the semi-autonomous plant systems
  - store of all this information and make it available to the ITER partners

ITER plasma control system

- the ITER Plasma Control System (PCS) has the overall control of an ITER pulse, including the fast (up to 500μsec) control of all the plasma feedback loops, such as:
  - plasma shape and position
  - plasma heating and current drive systems
  - **plasma instabilities by real-time feedback control**
  - plasma instabilities by real-time discharge optimisation
  - overall plasma fusion performance

AN EXAMPLE OF APPLICATION OF SPARSE REPRESENTATION METHODS TO ITER: OPTIMIZATION OF THE MAGNETIC DIAGNOSTIC SYSTEM FOR AEs

ITER measurement concept for magnetics



- ~2'000 sensors
- frequency range: 1kHz to 1MHz
- raw signal range: mV to kV

- digital or analogue integrators
- amplifiers

- slow (100kHz) ADCs for MHD equilibrium
- fast (1MHz) ADCs for MHD instabilities
- 16 bit resolution
- event triggering to manage data quantities

- data stored for specialist off-line studies
- additional, more specialised, event triggers
- real-time signals for MHD feedback control
- real-time signals also distributed to other plant systems
- on-line validation check and corrective action

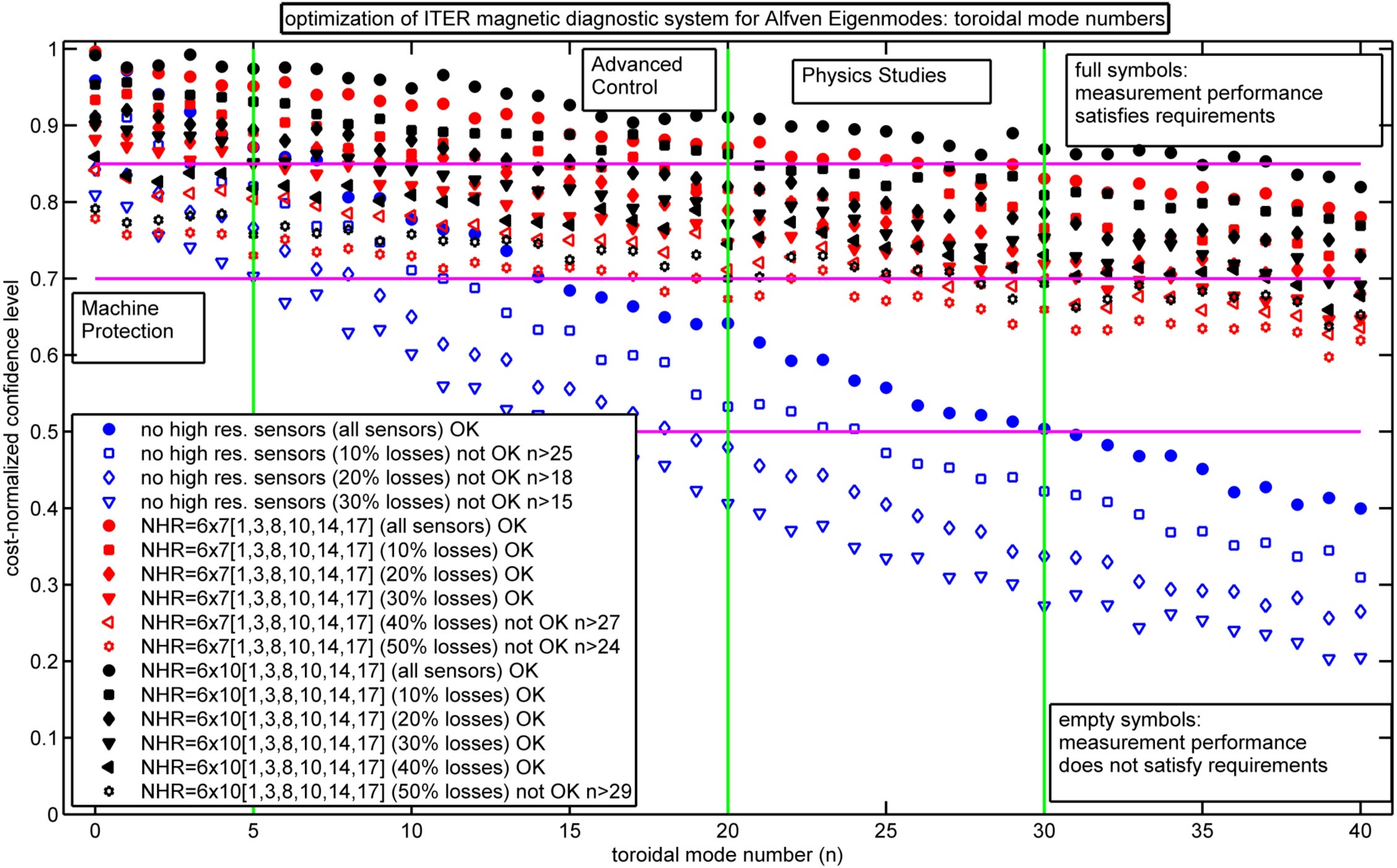
design of the ITER magnetic diagnostic system for AEs: must use universal system optimization strategy

- what are the tests that we need to perform on the measurement performance of the ITER magnetic diagnostic system for AEs?
  - **tests on sensitivity to noise in the measurements** ➔ can random noise be mistaken for real modes?
  - **tests on false alarms** ➔ modes that are not in the input spectrum but that will trigger a control reaction to “save” the plasma if they are wrongly detected
  - **tests on importance of missing sensors** ➔ resilience of the measurement performance against the loss of sensors (30 years life time, no access to replace faulty sensors)
  - **tests on installation and calibration errors** ➔ how sensitive is the measurement performance of the selected diagnostic system against such errors?
  - ITER measurement requirements used to define <u>correct</u> and <u>wrong</u> detection of the modes
- **all these tests are performed by optimizing the diagnostic’s spectral window**

➔ **<u>Sparse Representation Method!</u>**

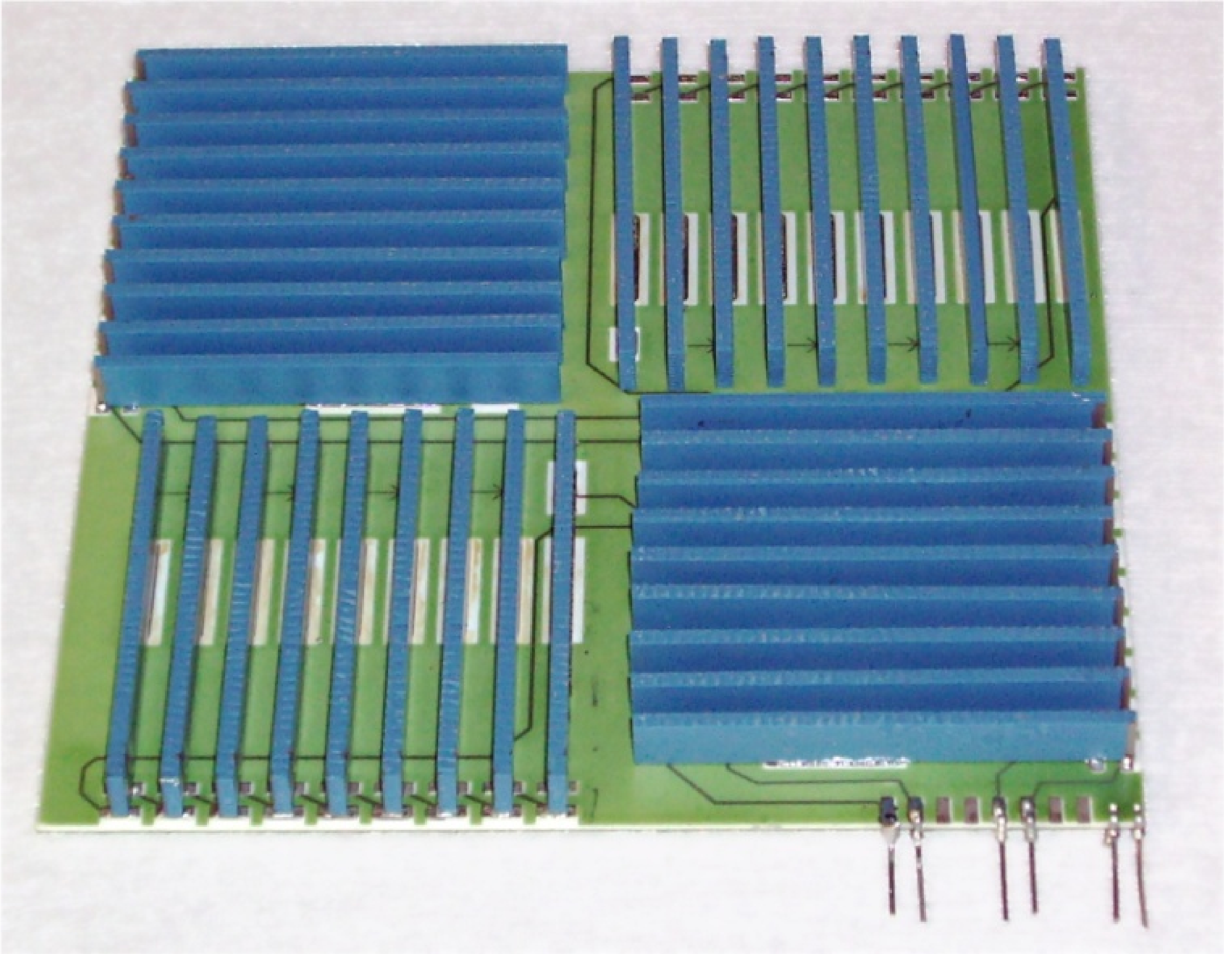
- **... and integrating engineering, risk management and financial requirements ...**
- **... and designing the best possible sensor for this task ...**

one example: toroidal mode number identification



producing a magnetic sensor that satisfies ITER measurement requirements for Alfvén Eigenmodes

- frequency range: from 1kHz up to at least 500kHz (possibly 1MHz)
- mode amplitude range to be detected: ~1mG<$|\delta B_{MEAS}|$<~1G, 10^{-7}x to ~10^{-4}x ITER ambient B-field
- compact 3D measurement geometry
- must withstand ~250deg temperature rise and high neutron flux >10^{17}/sec
- must last for 30 years
- must not pollute the plasma if broken
- <u>**low-temperature co-fired ceramics**</u>
  - our development at CRPP and EPFL
  - currently used in many industries
  - a novel technology in thermo-nuclear fusion plasmas



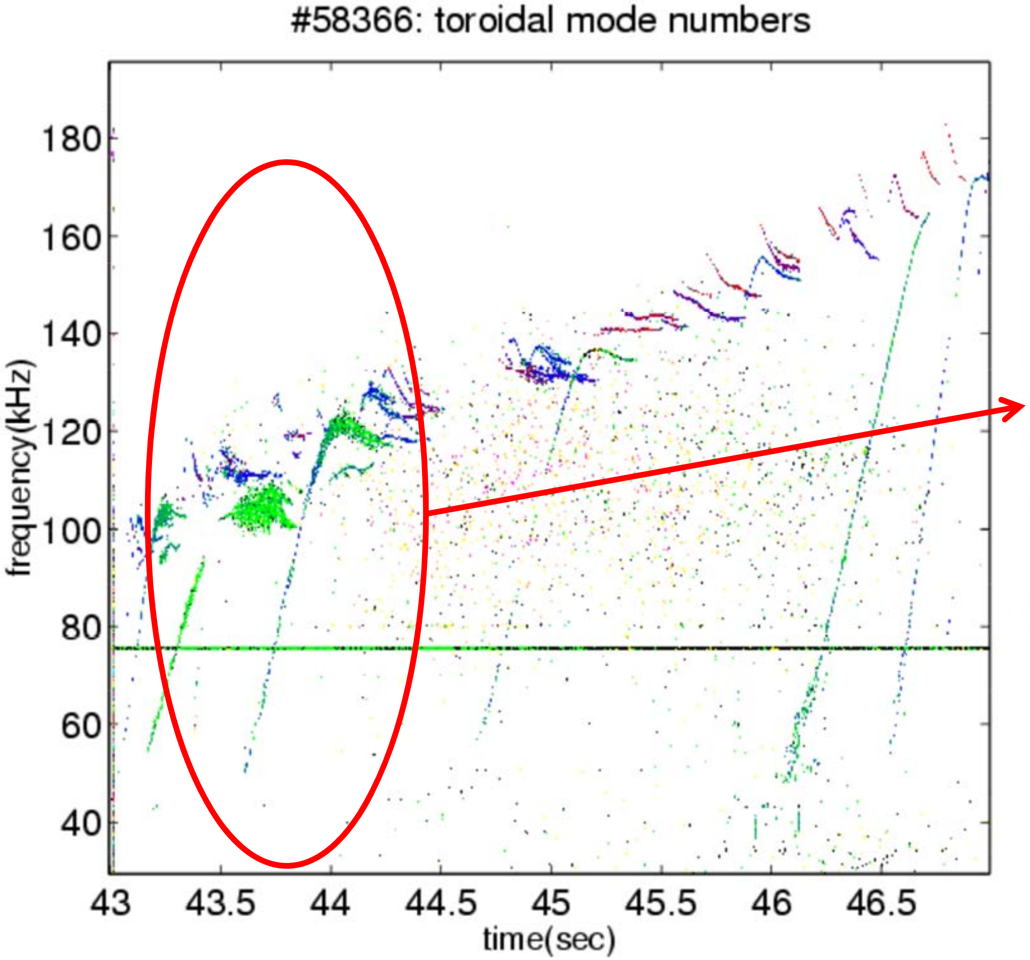
summary, conclusions, points for discussion

- **combining knowledge from different fields**
  - mathematical theory of Sparse Representation, astrophysics and thermo-nuclear fusion plasmas, real time computing for data analysis, nuclear plant safety and control, economics
- **allows to tackle one of the most difficult challenges in thermo-nuclear fusion plasmas**
  - detecting MHD instabilities that can affect the fusion energy gain
  - *detecting MHD instabilities that can provide information on background plasma properties*
- **performing efficient and accurate real-time analysis**
  - on a sub-millisecond time scale
  - using very limited CPU and RAM resources (1GHz PowerPC and 512MB RAM)
  - using a very limited number of measurements (up to 8 samples at every time point, limited by RAM)
- **and system optimization analysis**
  - including scientific, engineering, technological and financial requirements
  - example: the foreseen magnetic diagnostic system for AEs in ITER
- **this demonstration opens clear possibilities for real-time studies in present and future complex engineering and physical systems**
  - JET, ITER, SKA, ...
- **... and in fields far apart where funding is the most severe issue ...**

  ➔ archaeological prospection conducted by a volunteering organisation in Italy

possible future applications: GPUs for real-time magnetic spectroscopy

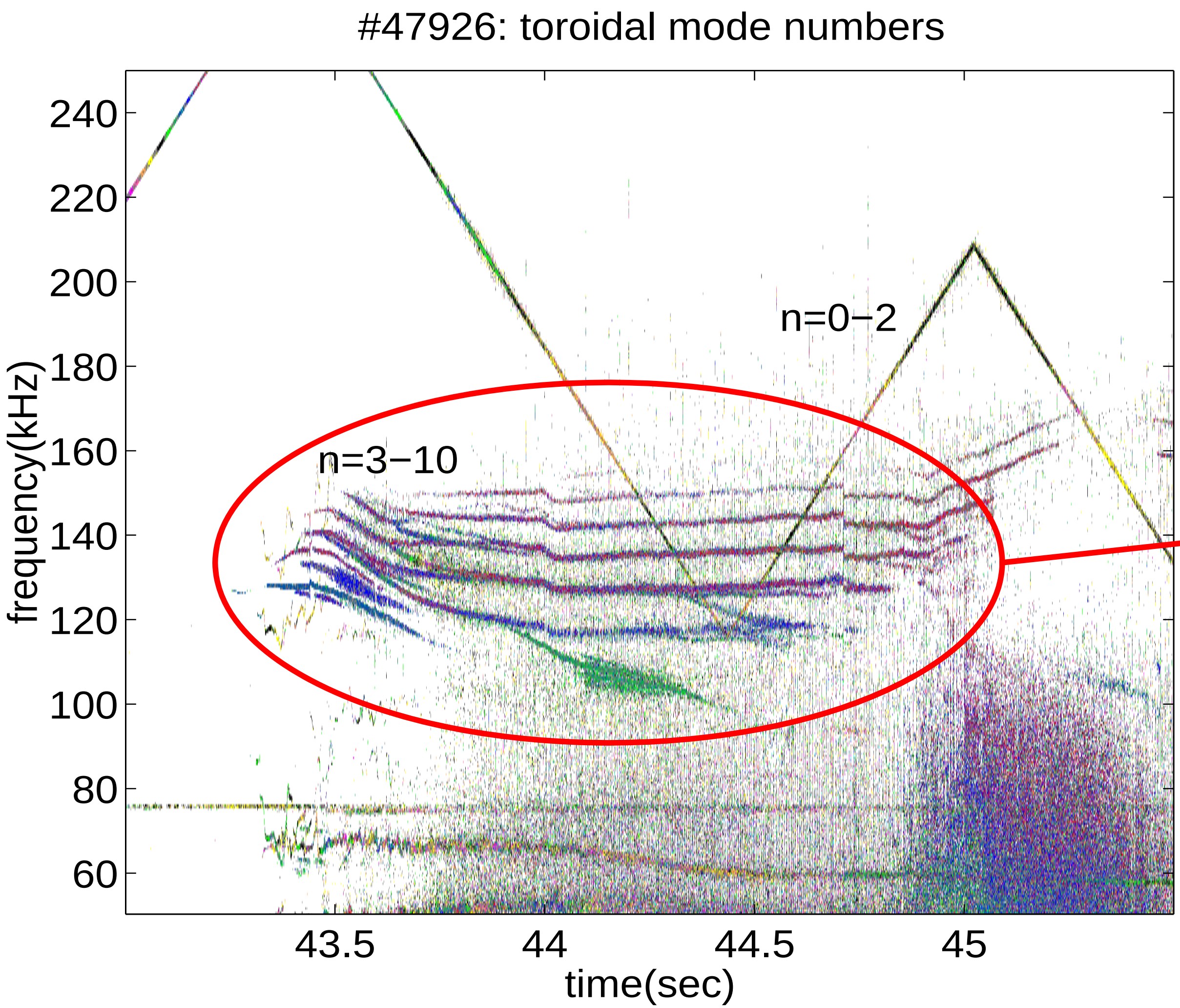
- Alfvén Cascades in JET plasma with non-monotonic current profile
- we must control current profile to achieve good confinement of αs!



- this hockey-stick pattern in Alfvén Cascades allows determining the value and the location of the minimum point in the safety factor profile
- need accurate measurement of mode characteristics for real-time diagnostic applications

possible future applications:
GPUs for real-time magnetic spectroscopy

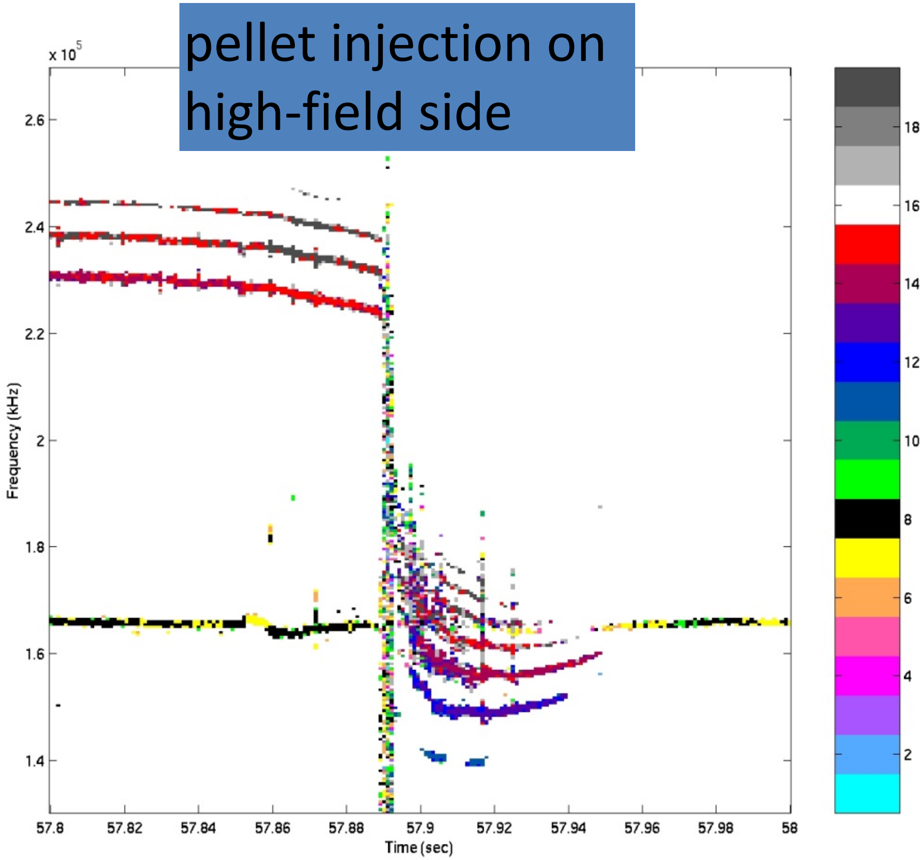
- attach GPUs to image pixels, process signal to recognise certain patterns using Sparse Representation ➔ obtain information to be used for active MHD control

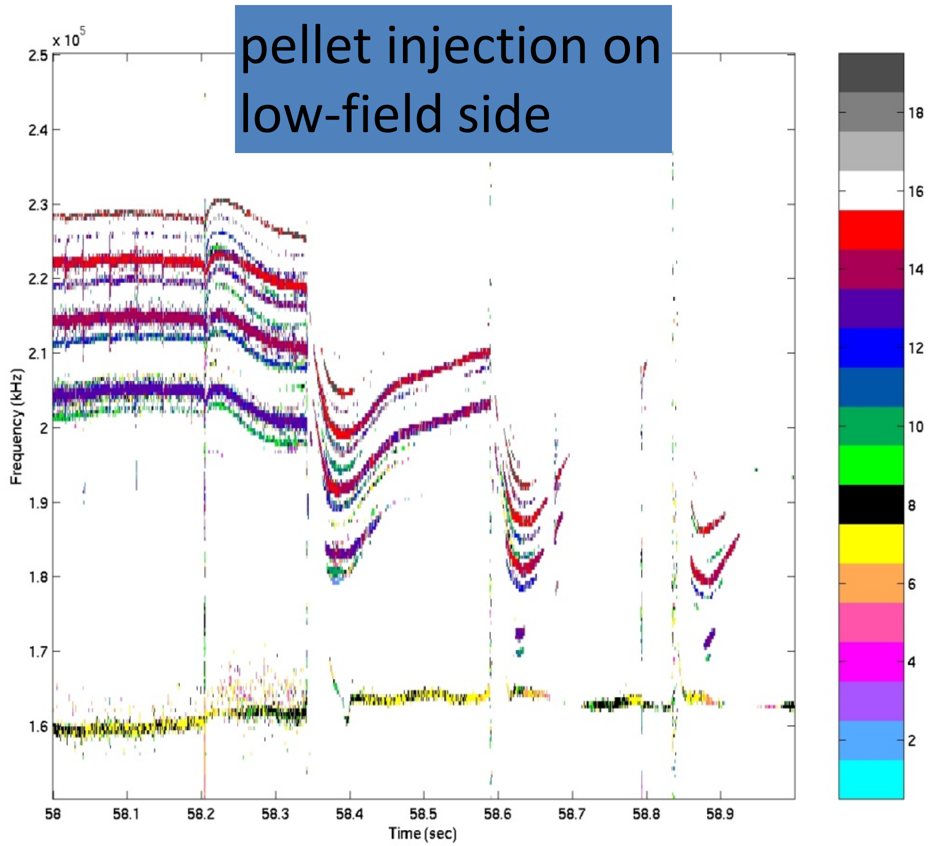


this pattern for AEs allows measuring the toroidal plasma rotation from the Doppler shift in frequency for the different n-modes

possible future applications: GPUs for real-time magnetic spectroscopy

- pellet injection: $(n/\Delta n)\Delta t \ll \tau_A \approx 10\mu s$ ➔ **v_A sweeps $f_{FAST}(v_{||},v_{\perp})$**
  - redistribution of MeV energy ions, affecting AEs dynamics

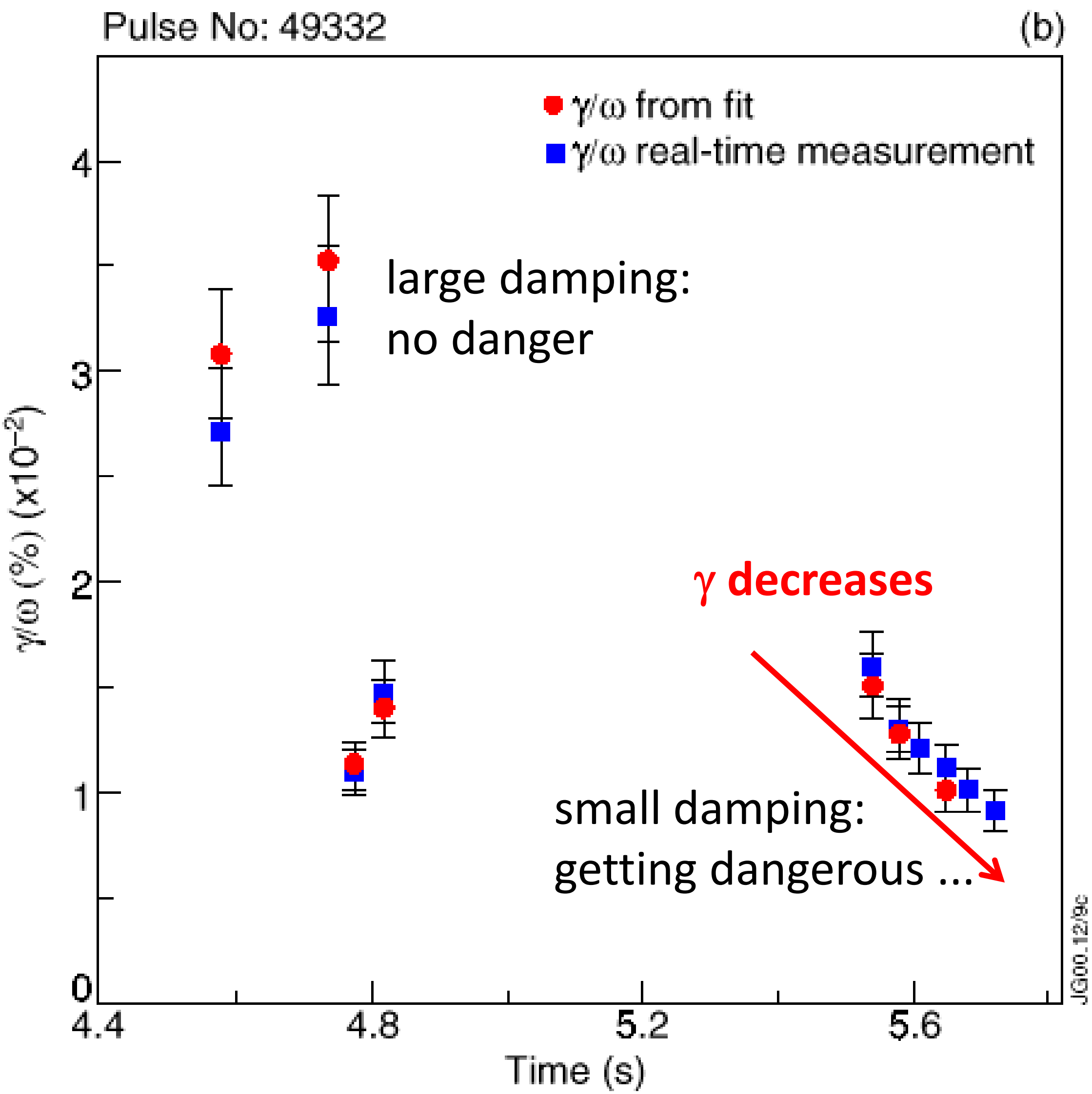




- this pattern in AEs allows measuring the fuelling efficiency at the mode location in real-time ➔ frequency drop for different modes $\propto 1/\sqrt{\Delta n}$ at mode location

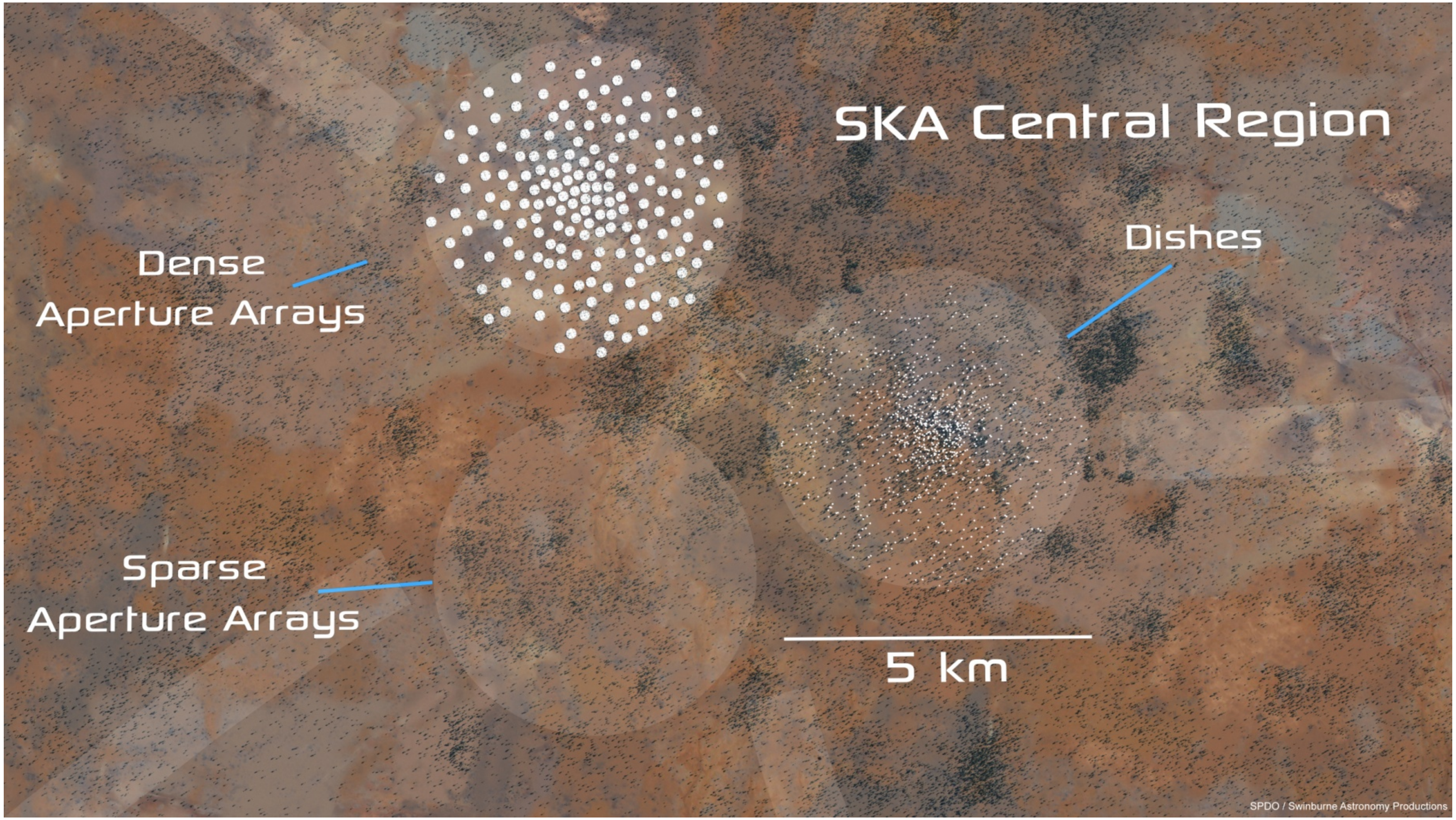
possible future applications: real-time control of AE stability

- generate a control signal related to proximity to marginal stability limit (γ=0)
  - measurement of γ exists already in the JET real-time signal server via the AELM…



- when damping too small, approaching limit γ=0 ➔ use actuator(s) to get further away from marginal stability limit γ=0
- reaction time: from 0.1ms to 5ms depending on actual value of γ and dγ/dt
- real-time feedback on plasma parameters (edge shape, heating waveforms, ...)

possible future applications:
"real-time" data analysis for the SKA with GPUs

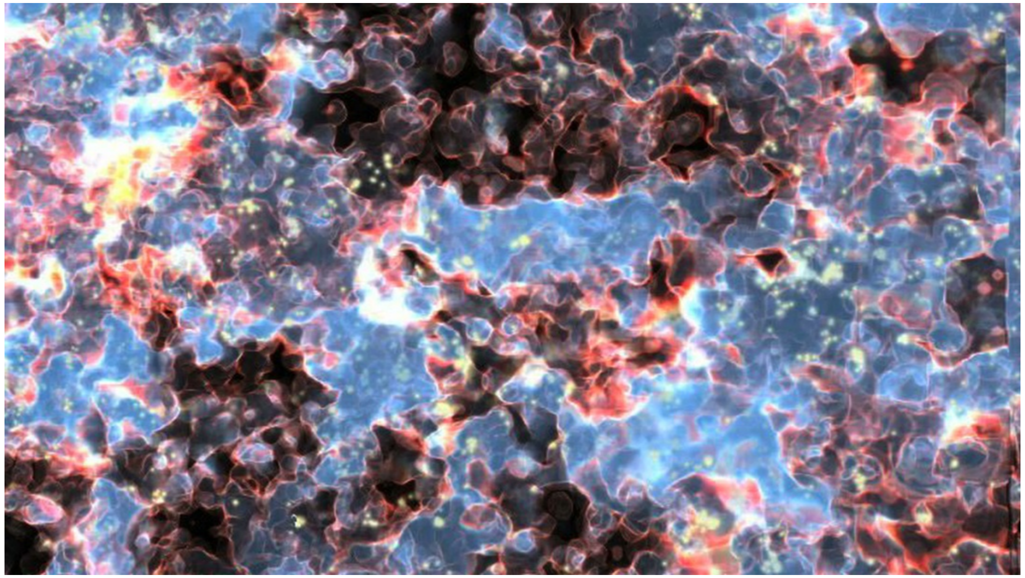


- the SKA will be able to survey the sky more than ten thousand times faster than ever before
- the SKA central flexible design will enable exploration of the unknown

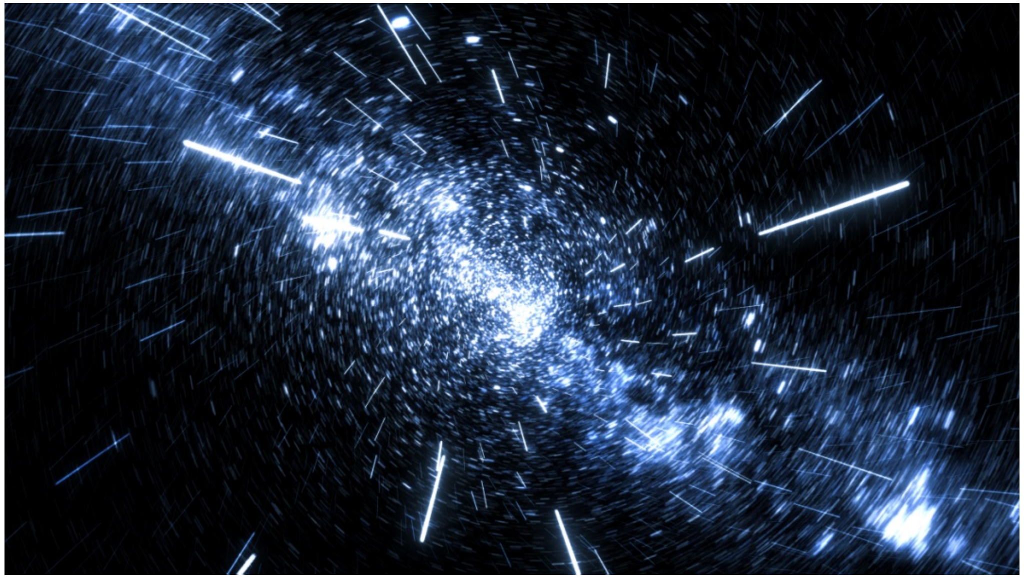
- image credits: SPDO/Swinburne Astronomy Productions (SKA website)

possible future applications: “real-time” data analysis for the SKA with GPUs

- the SKA central computer will have the processing power of about 1 billion PCs
- the SKA will generate enough raw data to fill 15 million 64 GB iPods every day!
- the SKA super computer will perform 10^{18} operations per second – equivalent to the number of stars in three million Milky Way galaxies – in order to process all the data that the SKA will produce
- “real-time” data analysis: GPUs associated to image pixels, process data to recognise patterns, change telescope settings for next images a few days afterwards...



the epoch of re-ionisation



acceleration in the expansion of the Universe

- all image credits: SPDO/Swinburne Astronomy Productions (SKA website)

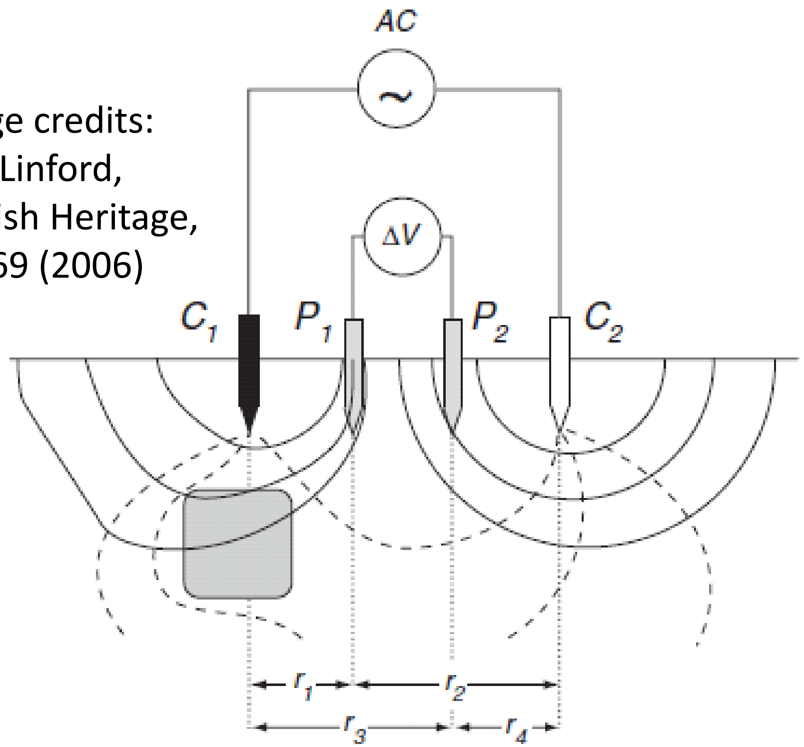
possible future applications: archaeology

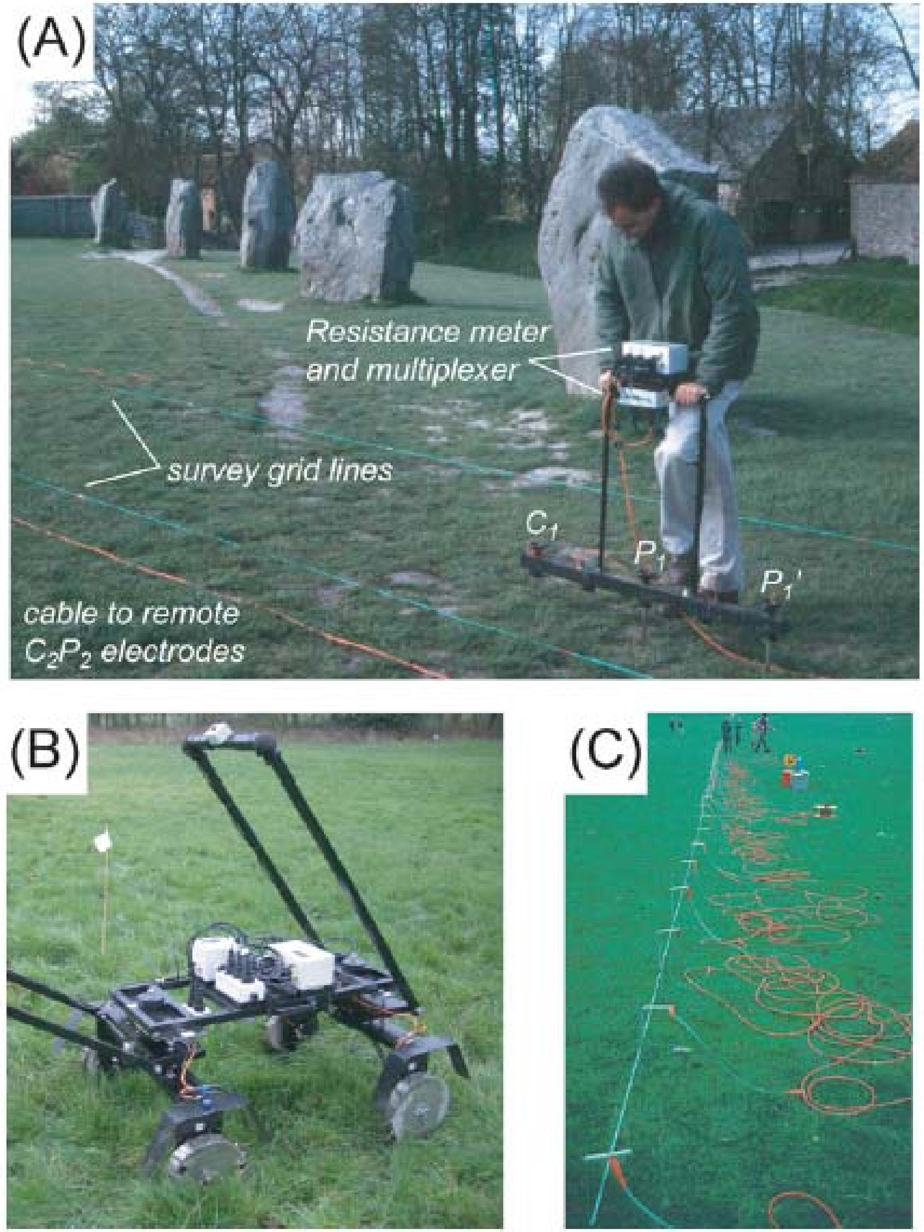
- electrical prospection: use a network of current sources to measure underground electrical resistivity → detect anomalies
  - very efficient method for oil/gas field prospection: the Schlumberger diagram
  - analysis is very complicated and requires very advanced hardware and software
  - only companies like Shell, Exxon, BP ..., can do this analysis efficiently using proprietary software and super-sophisticated hardware
- often tried in archaeology but seldom successfully due to the hardware investment required when the software is not sufficiently sophisticated
  - two good examples: Pompei and Tell Megiddo (→ *does this name ring a bell?*)
- electrical anomalies ≡ underground structures ≡ patterns of walls and/or vacuums (chambers) and/or isolated big objects
- **idea: measure resistivity at different depths, subtract mean value over grid and/or along individual axis, use Sparse Representation to find periodic patterns**
  - remains of buildings walls
  - roads, junctions, tombs on the side
  - cavities arranged along an axis
  - *problems: structures not necessarily periodic ... nor regular on a measurement grid*

possible future applications: electrical prospection techniques in archaeology

- schematic showing a practical field system for the measurement of earth resistance
- shows the effect of a high-resistance feature buried beneath C1
  - distortion of the current flow around the object
  - distortion of the concentration of the equipotential contours at the surface around P1

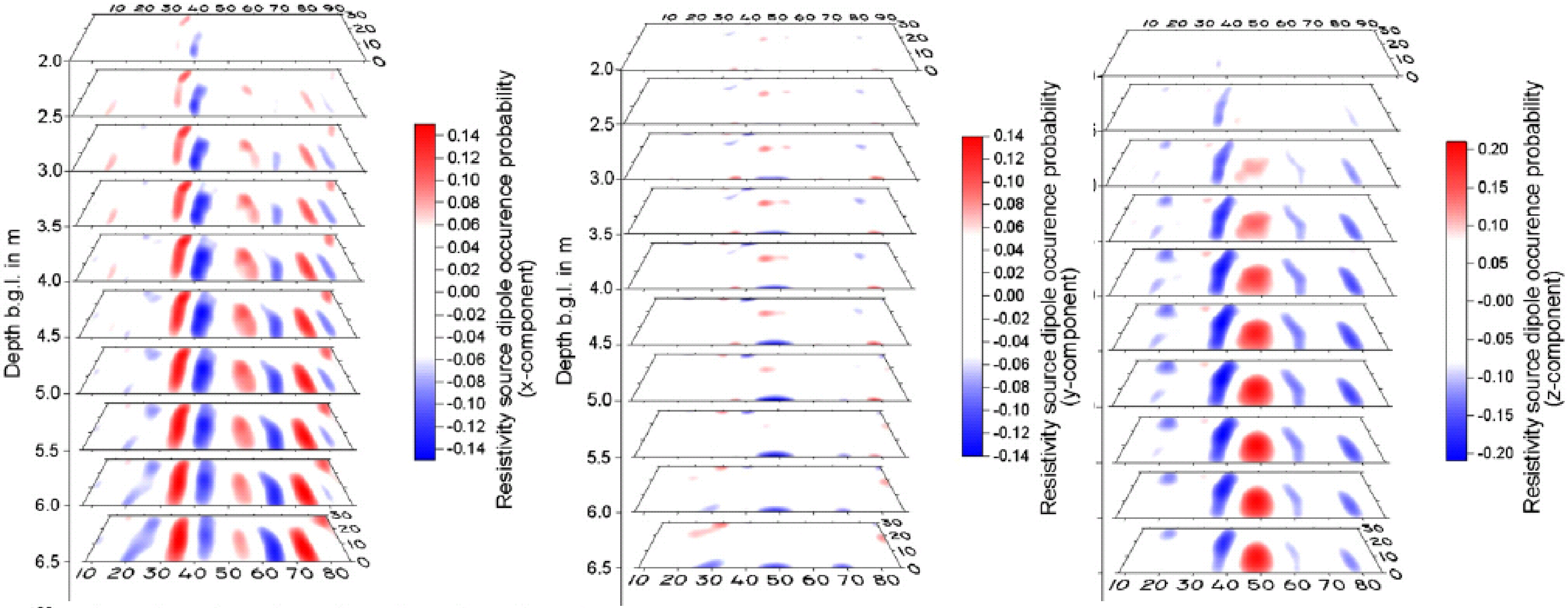
image credits:
Neil Linford,
English Heritage,
RPP69 (2006)

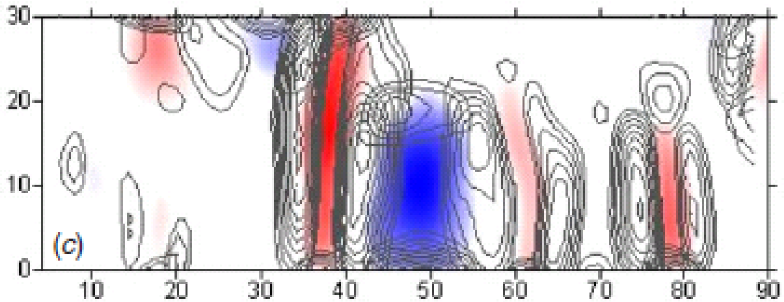




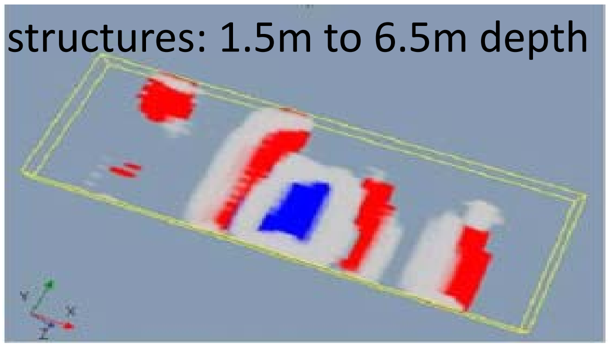
electrical prospection techniques in Pompei

3D electrical tomography of an insula in Regio III in Pompei [image credits: R.Alaia JGE5 (2008)]





xy-axis cut at 3.5m depth



- very sophisticated mathematical approach
- lots of personnel involved
- unsuitable for low-key (and un-funded) projects

Etruscan fortress town of Rofalco

- a military outpost for the Etruscan town of Vulci during their wars against Rome
- controlling the access road through the valley of Lamone
- site now completely covered by a rather thick forest ...
- ... which is now a natural reserve, cannot just cut trees and dig wherever ...
- ... but we would like to develop the site for local tourism: how can we do this?

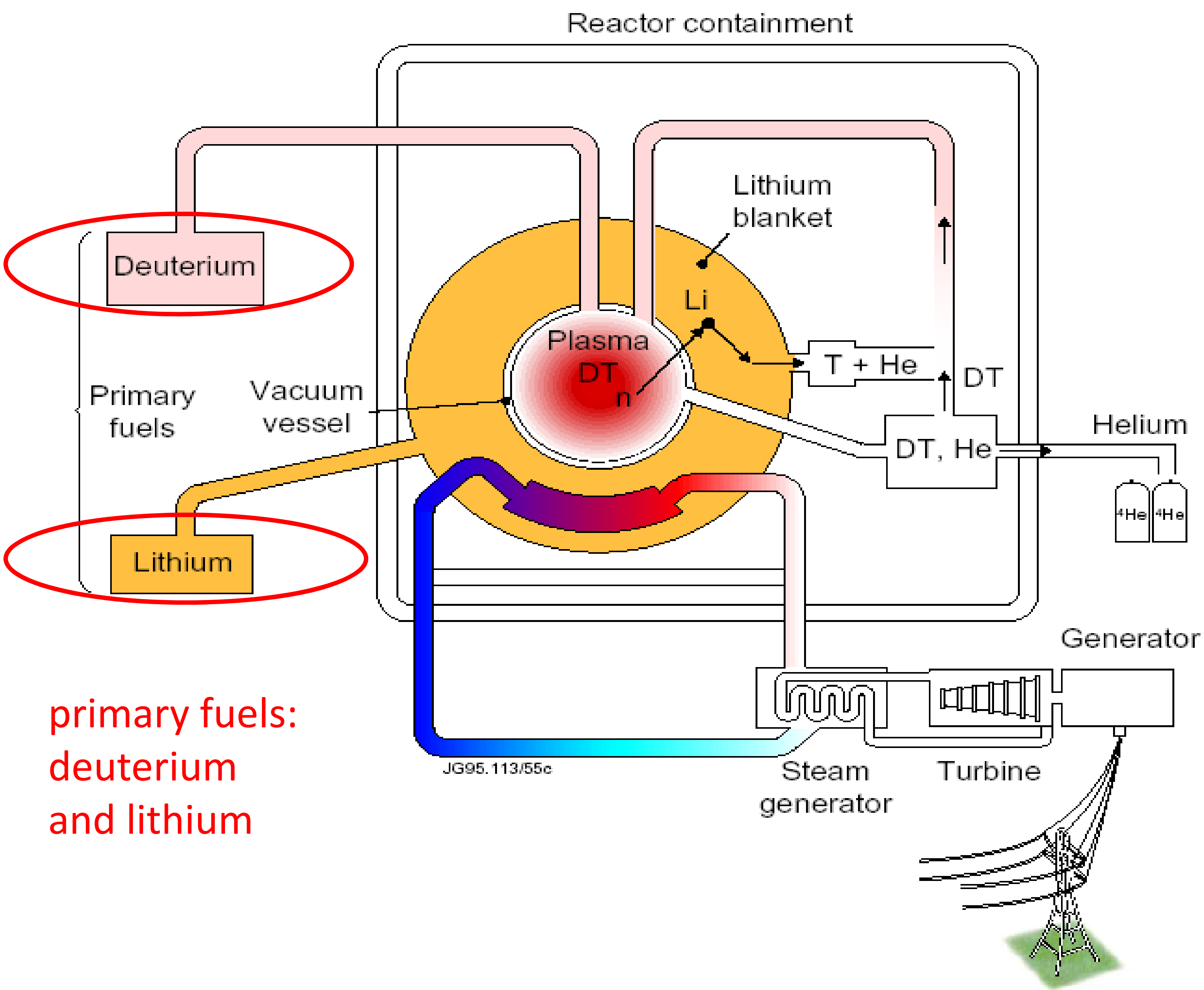
proto-Villanovian necropolis of Poggio della Pozza

- Poggio della Pozza: pre-Etruscan necropolis, first used ~1200BC until ~500BC
- looking for a “ziro”: huge carved-out stone egg (2m tall, 1m wide), set underground in an isolated position
- inside the ziro there is a ceramic urn (“canopo”) with the dead’s ashes and a few objects
- often smaller ziri around main one (➔ family members)

THANK YOU VERY MUCH FOR YOUR ATTENTION!

QUESTIONS? SUGGESTIONS?

schematic of a thermo-nuclear fusion power plant

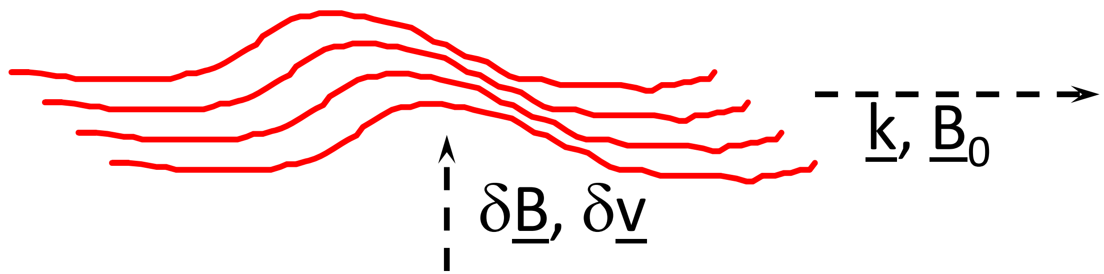


primary fuels: deuterium and lithium

- advantages of thermo-nuclear fusion energy:
- **high energy density fuel**
  - 1g DT → 26MW-hr
  - 1g coal → 0.003kW-hr
- **abundant fuel**
  - D is 1/6500 of H
  - ^{6}Li is 17ppm of crustal rock
- **environmental**
  - no CO_2 emission
  - no high-level nuclear waste
- **no risk of nuclear accidents**
  - <5min of fuel in reactor
- **no generation of weapons material**
- little use of land
- not subject to local or seasonal variations

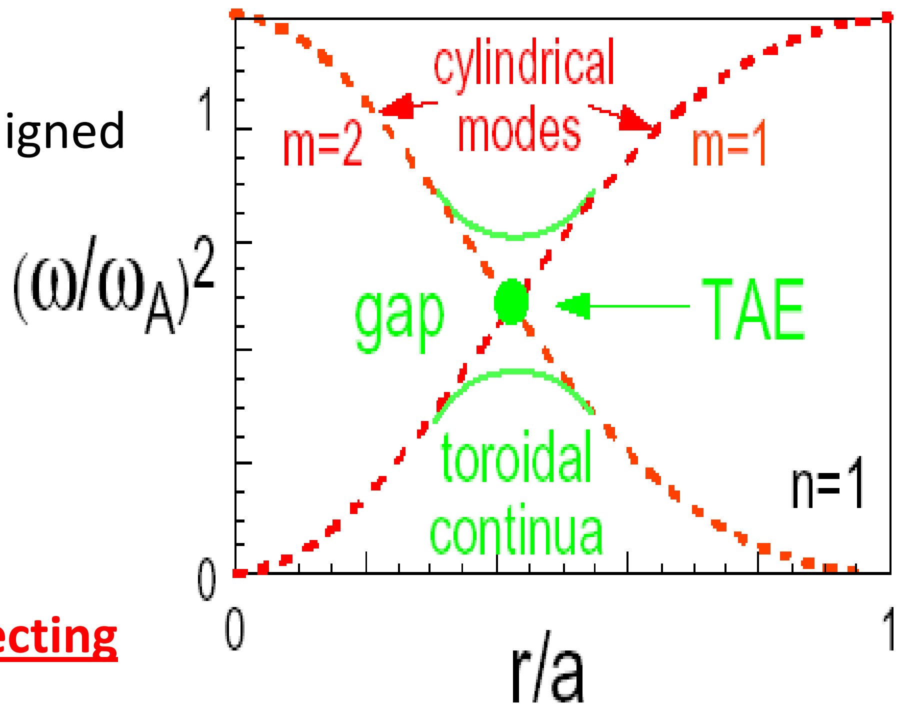
an example of *benign* instabilities in tokamaks: Alfvén waves and Alfvén Eigenmodes

B-field and plasma frozen together: field lines ≡ strings with tension and inertia ➔ Alfvén wave propagation



- in a cylinder: a sea of Alfvén waves
  - Alfvén continuum: $\omega^2(r)=k_{\|}^2(r)v_A^2(r)$
  - no globally propagating wave
  - small scales ➔ strong damping
- in a tokamak: Fourier components $\propto\exp(-i\omega t)$ aligned with B-field periodicities $\propto\exp(im\theta) * \exp(-in\phi)$
- coupling of (cylindrical) poloidal harmonics:
  - gaps in continuum spectrum
  - weakly damped Eigenmodes in these gaps
- Alfvén Eigenmodes become unstable:
  - resonant interaction with fusion-born αs
- <u>**αs can drive unstable spectrum of AEs**</u>

➔ <u>**AEs then remove αs from the plasma core affecting plasma self-heating process**</u>



the Joint European Torus tokamak: a bit of history

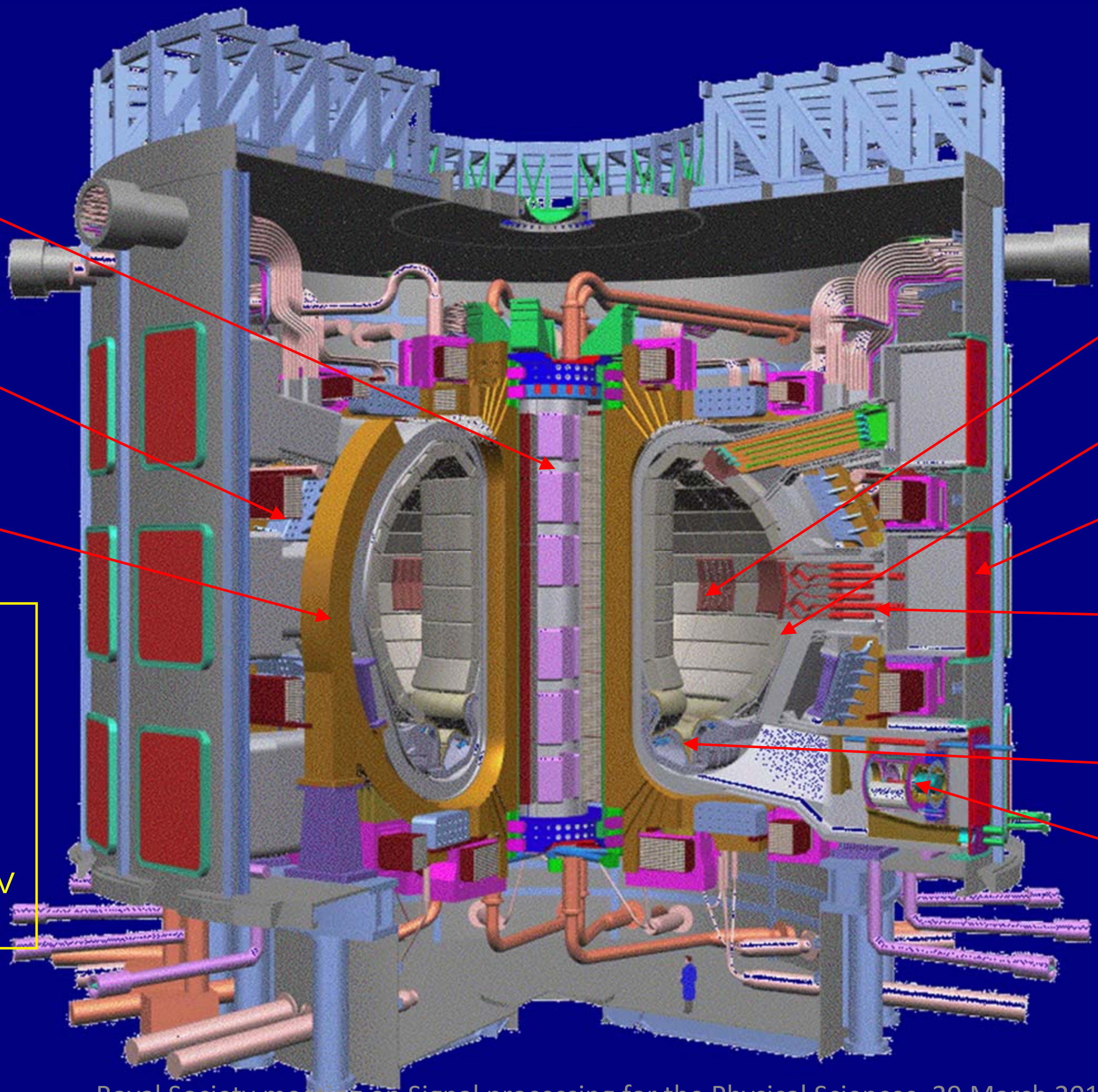
- JET working group formed in 1972
- JET foundation stone laid on 18th May 1979
- first JET plasma on 25th June 1983 at 13hr44: 27kA plasma
- 1MA plasma in October 1983
- world record 3MA plasma in December 1983
- **16MW DT-fusion world record obtained in 1997**
- **maximum fusion gain Q=0.65 transient, Q=0.35 steady-state**
- currently operating with a full metallic wall for scenario development in preparation of ITER operation
- a collaborative effort funded by the EU member states (+ Switzerland) with participants from around the world

main features of the ITER design

superconducting
central solenoid
^{3}NbSn, 6 modules

superconducting
poloidal field coil
NbTi, 6 modules

superconducting
toroidal field coil
^{3}NbSn, 18 modules



^{6}Li blanket module
440 modules

vacuum vessel
9 sectors

cryostat
24m high x 15m radius

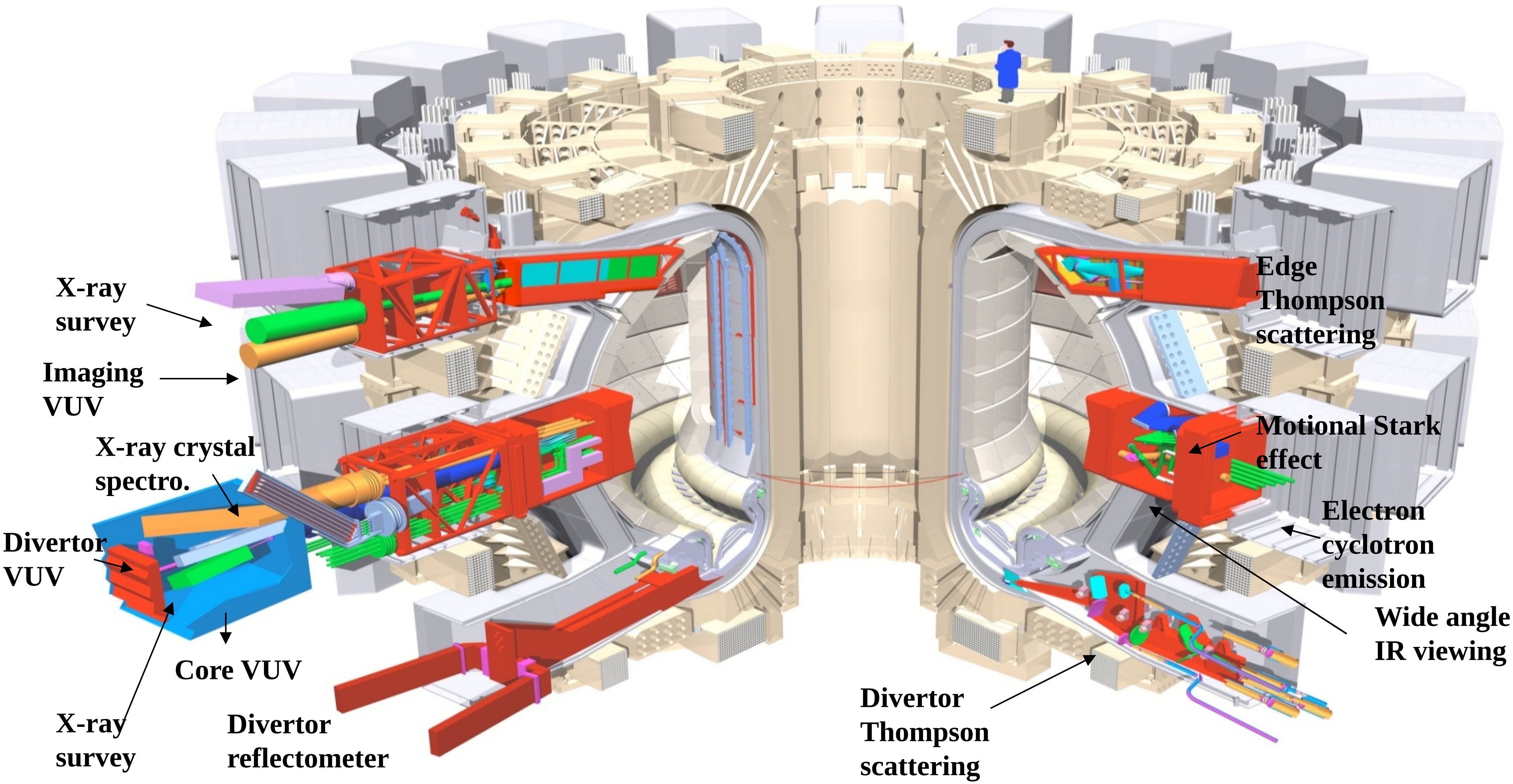
port plug
6 heating
3 test blankets
2 limiters/RH
diagnostics

divertor
54 cassettes

cryopump
8 units

typical parameters:
pulse length > 1000sec
fusion power: 500MW
fusion gain: Q=10
plasma volume: 850m^{3}
magnetic field: 5.3T
plasma current: 15MA
plasma temperature: 20keV
plasma density: 10^{20}m^{-3}

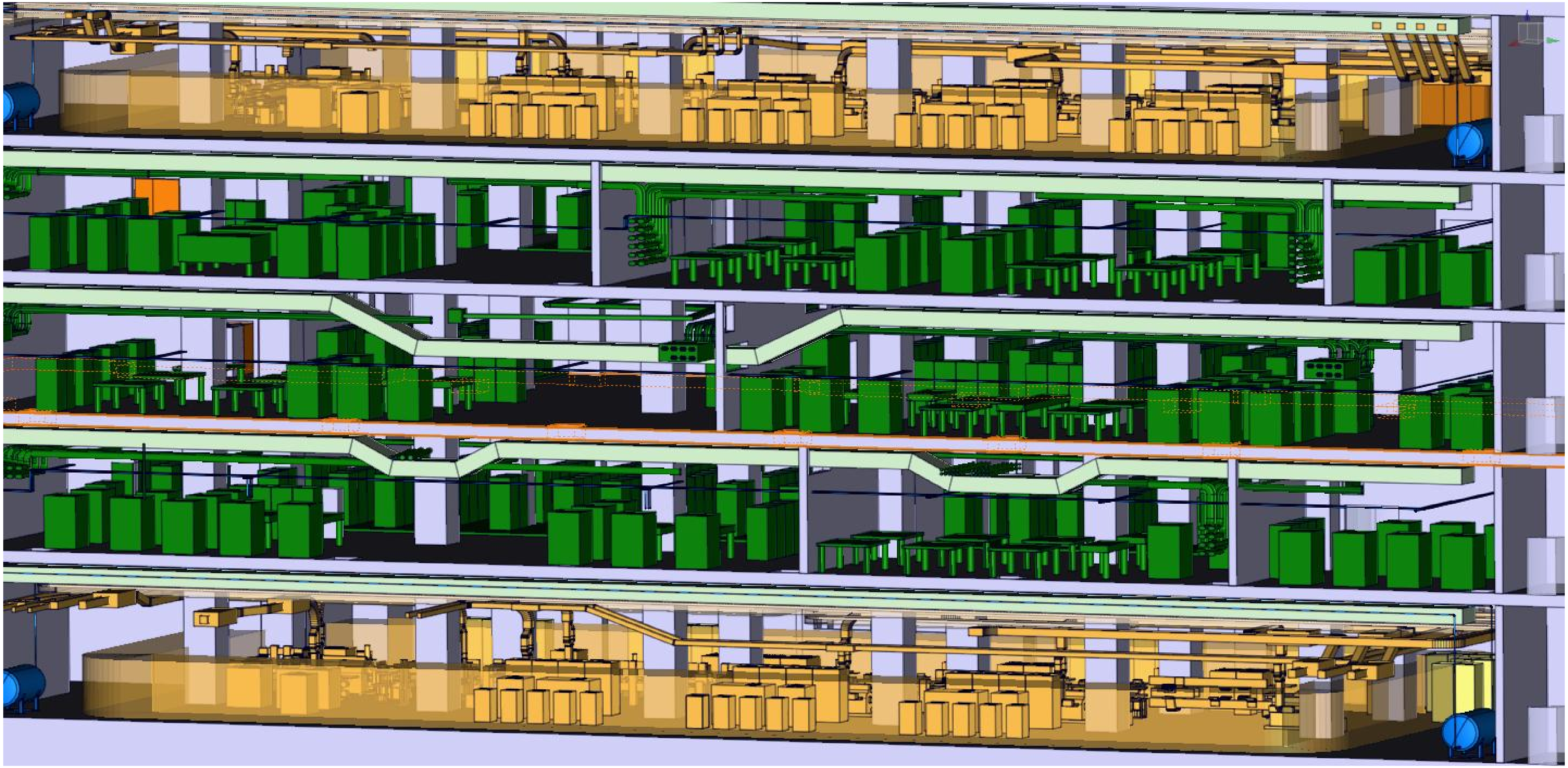
ITER diagnostics systems



- about **45 parameters** have to be measured for ITER operation
- in excess of 60TB of data for each standard ITER pulse of 1’000 seconds (+ high resolution images from cameras)
- detailed specifications for each one of the required measurements guide design of the system intended to obtain it

ITER diagnostic hall for instrumentation

- three floors for data acquisition equipment (~700 cubicles)
- two floors for associated services (cooling, low power feeds, ...)



data analysis requirements for ITER

- in order to prevent the plasma and auxiliary heating systems from damaging the internal components, measurements of key parameters will be needed in real time at very high reliability: first wall temperature, fusion power, etc ...

➔ **machine protection**

- many other measurements are needed to control the plasma in real time so that the required operating regime and plasma performance is achieved: plasma shape and position, plasma current, electron density, impurities, etc ...

➔ **plasma control**

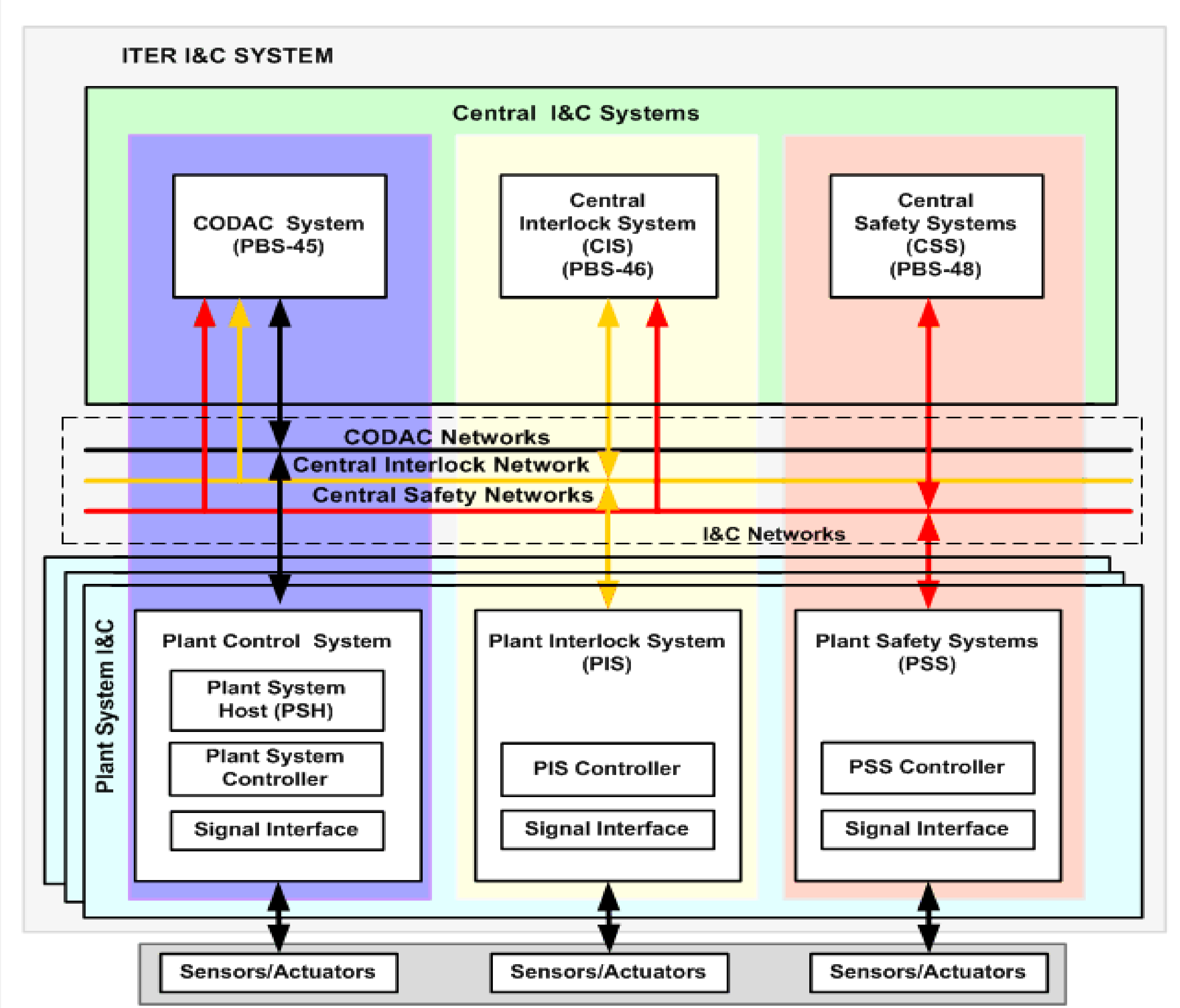
- additional measurements are needed for specific physics studies: confined and escaping alpha particles, turbulence, MHD instabilities, etc ...

➔ **physics studies**

- about **45 parameters** have to be measured for ITER operation
- expecting in excess of 50TB of data for each ITER pulse of 1’000 seconds
- physics and engineering integration: detailed specifications for each parameter to be measured guide the design of the corresponding diagnostic systems

ITER Control-Command architecture

the instrumentation and control architecture cleanly reflects its three missions (**nuclear safety**, **protection of investment**, **experiment**) and its two layers (equipment from **on-site** project team and **external** partners)



ITER diagnostics archiving needs

- the diagnostics archiving needs are considered to dominate the overall scientific archiving requirements for ITER
- criteria used for estimate:
  - number of signals and variables
  - measurement update rate and signal sampling rate
  - need for archiving of raw data
  - data rates dominated by a few diagnostics
  - identified dominating data sources and estimated remaining sources

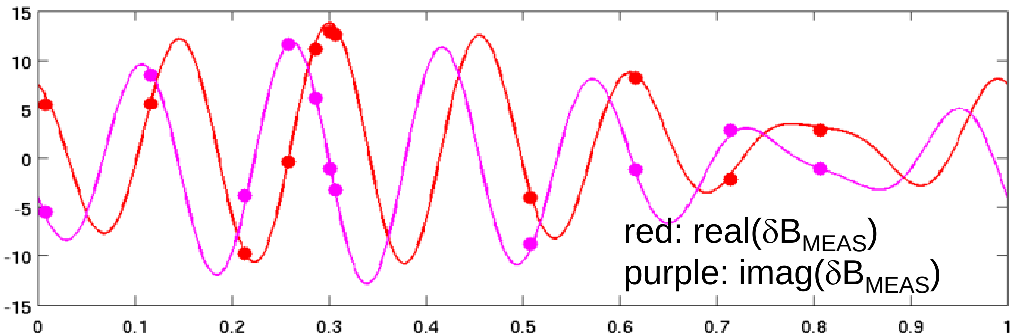
streaming mode	**first plasma (2019)**	**physics exploitation (>2022)**
continuous streaming during pulse (1’000 seconds)	**2 GB/sec**	**50 GB/sec**
event-triggered on demand streaming (3 seconds)	**10 GB/sec**	**300 GB/sec**

ITER measurement requirements for MHD modes

- frequency range: from below 10kHz up to at least 500kHz
- mode amplitude: $|\delta B_{MEAS}|$ from <1mG to ~1G ($<10^{-7}$ to $\sim 10^{-4}$ the ambient magnetic field in ITER)
  - acceptable relative error $\Delta(|\delta B_{MEAS}|)<30\%$ for $|n|\leq 3\rightarrow 5$ (if modes to be used for real-time control ➔ trend over the discharge)
- toroidal mode number to be detected: $|n|<20\rightarrow 30$
  - acceptable error $|\Delta n|=0$ for low-n modes $|n|\leq 5$ ➔ real-time control
  - $|\Delta n|\sim 1\rightarrow 3\sim 10\%$ for higher-n modes ➔ physics studies
- poloidal mode number to be detected: $|m|<20\rightarrow 30$
  - acceptable error $|\Delta m|\leq 0$ for low-m modes $|m|<5$ ➔ real-time control
  - $\sim 10\%$ error on $m/n=q$ for real-time application of MHD spectroscopy
  - $|\Delta m|\sim 2\rightarrow 5\sim 20\%$ for $|m|>10$ ➔ physics studies

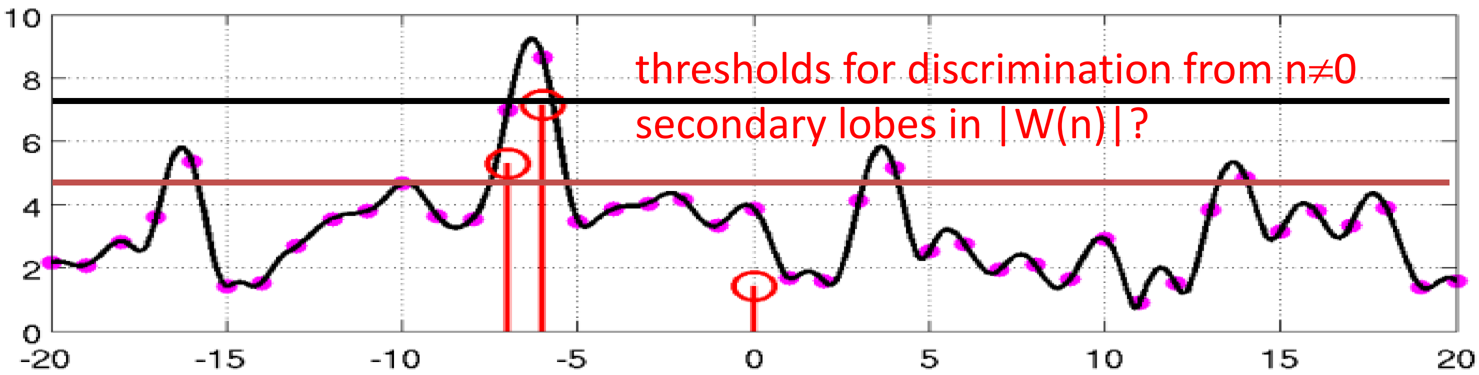
why do we need to correctly interpret the spectral window?

- toroidal periodogram: convolution of the input mode spectrum with the **Spectral Window $W(n) = \Sigma_k \exp(i2\pi\phi_k n)$** related to the sensors' positions ϕ_k
- an example using JET simulated data:



input data mapped onto the full set of 11 HF **non-optimized** magnetic sensors

spectral window |W(n)|: high n≠0 secondary lobes underlying regularity of sensors' position



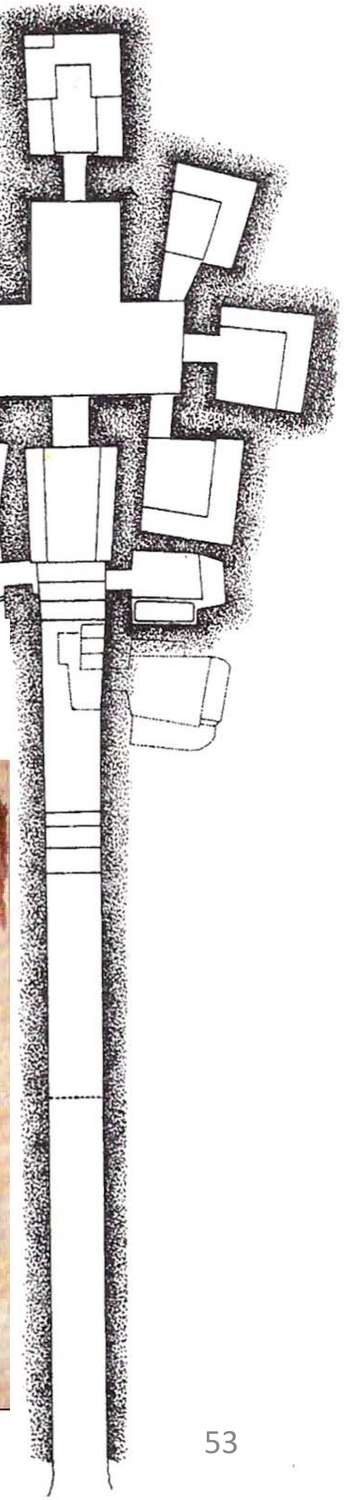
periodogram: the red circles are the input modes, how to discriminate reliably between all possible solutions (purple dots) obtained with a non-optimized spectral window?

Via degli Inferi a Cerveteri

- Via degli Inferi a Cerveteri: Etruscan necropolis (~600BC to ~200BC)
- see D.H.Lawrence, Etruscan Places, (1932) for more info
- first excavated by GAR (1982 to 1994)

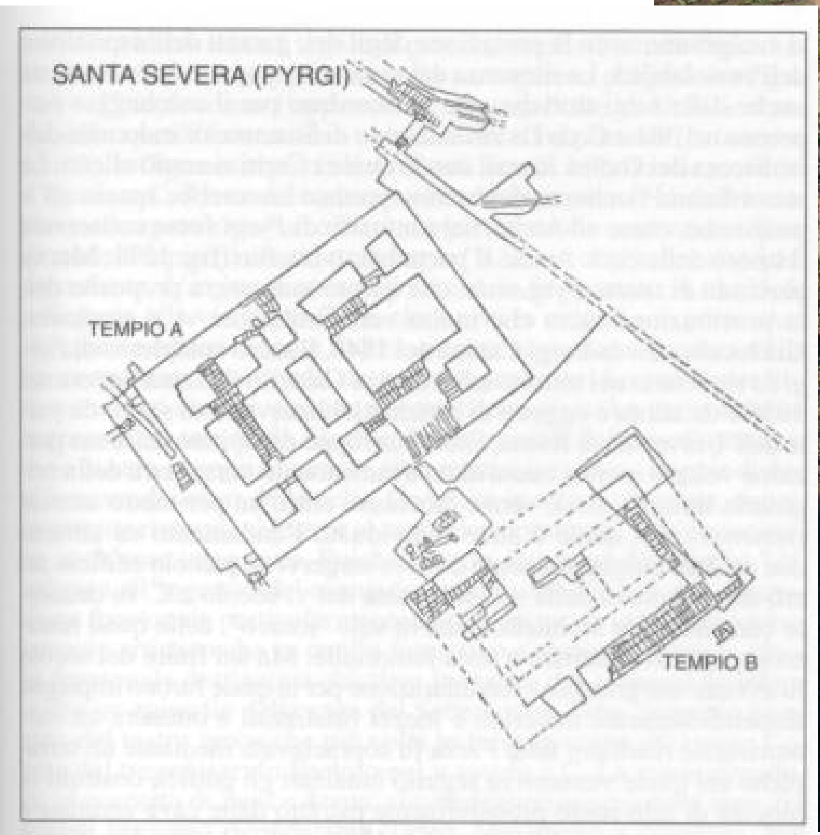
tomba François in Vulci

- Tomba François in Vulci, dating around 375BC
  - see D.H.Lawrence, Etruscan Places (1932) for more info
- belongs to the Etruscan family of Seties
- discovered in 1857 by Alessandro François
- famous for the frescos of the Orazi and Curiazi
  - ➔ *does this ring a bell?*



Etruscan and Roman town of Pyrgi

- Etruscan town founded ~500BC
- famous for the Pyrgi Tablets, which allowed a partial understanding of Etruscan through Phoenician
- plundered by Dyonisius in 384BC
- Roman colony established in 191BC



Via Amerina close to Falerii (now Civita Castellana)

- Roman consular road laid around 220BC crossing Umbria from north of Latium
- often a necropolis on the side of the road
- on areas that are privately owned
- and on which residential building permission is being sought

Ripa Maiale, close to Cencelle

- natural source, with presence dating from Neolithic age (<3000BC) to Hellenistic temple (~200BC) to medieval aqueduct (~1200AD) serving the town of Cencelle (ancient Roman Town of CentumCellae)